Consortia Research Platform on Conservation Agriculture:
Fifteen Years of Tillage and Residue Management in Rice-Wheat System

ICAR-Central Soil Salinity Research Institute
Karnal-132001 (Haryana) India
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FORWARD

India's agricultural sector, though a cornerstone of the national economy and food security, is currently confronting formidable challenges. Issues such as soil degradation, water scarcity, environmental pollution, and stagnating productivity are being compounded by climate change and shrinking arable land. The rice-wheat cropping system of the Indo-Gangetic Plains, once hailed as a driver of the Green Revolution, is now exhibiting signs of fatigue due to unsustainable practices like intensive tillage, residue burning, and inefficient input use. Addressing these challenges requires innovative, sustainable, and scalable approaches. Conservation Agriculture (CA) offers a promising solution by promoting minimal soil disturbance, residue retention, and crop diversification—principles that improve soil health, reduce greenhouse gas emissions, and enhance water and nutrient use efficiency. The adoption of CA is central not only to improving farm profitability and environmental health but also to achieving the Sustainable Development Goals (SDGs) that guide global development priorities.

Recognizing the potential of CA, the Indian Council of Agricultural Research (ICAR) launched the "Consortia Research Platform on Conservation Agriculture (CRP on CA)" in 2015–16. As part of this initiative, the ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal implemented the project entitled "Productive Utilization of Salt Affected Soils through Conservation Agriculture" with a focus on the rice–wheat system in salt-affected regions. This technological bulletin presents key insights and outcomes from this long-term research effort. It highlights the potential of conservation tillage, direct seeding, crop residue management, and improved machinery such as the Turbo Happy Seeder and combined harvester in enhancing resource-use efficiency, restoring soil health, and building climate resilience in rice–wheat systems. The findings serve not only as scientific evidence but also as practical guidance for policymakers, researchers, and farmers striving for sustainability. I commend the dedicated efforts of our scientists, collaborators, and support staff who contributed to this research. I hope that this bulletin serves as a valuable resource in furthering the adoption of conservation agriculture in India's salt-affected and resource-constrained regions.

(RK Yadav)

PREFACE

Agriculture stands as the backbone of India's economy, sustaining over half of the nation's population and providing critical support to agro-based industries. However, the twin challenges of dwindling arable land due to urbanization and industrialization, coupled with the adverse effects of climate change and unsustainable farming practices, threaten long-term agricultural productivity and food security. In this context, conservation and judicious management of natural resources are essential to safeguard the future of Indian agriculture.

Conservation agriculture (CA) has emerged as a transformative approach to address these pressing challenges. By advocating minimum soil disturbance, permanent soil cover, and diversified crop rotations, CA fosters ecological balance, enhances soil health, optimizes input use, and improves system resilience to climate variability. This scientific bulletin encapsulates the learnings from a landmark long-term experiment *"Fifteen Years of Tillage and Residue Management in the Rice-Wheat System"*—undertaken at ICAR–Central Soil Salinity Research, Karnal, under the ambit of the Consortia Research Platform on Conservation Agriculture (CRP on PC), ICAR, New Delhi.

The bulletin synthesizes the outcomes of diverse tillage and residue management strategies—conventional, reduced, and zero tillage; crop residue incorporation and retention; puddled transplanted and direct-seeded rice; and zero tillage wheat—evaluated primarily in the western Indo-Gangetic Plains. The findings offer critical insights into improving system productivity and profitability while mitigating greenhouse gas emissions and managing water, carbon, and energy footprints. This publication also highlights significant infrastructure developments, research tools, and key publications resulting from the project.

We gratefully acknowledge the pioneering vision and support of Dr. DK Sharma, Dr. PC Sharma and Dr. RK Yadav, Former Directors of ICAR–CSSRI, for laying the foundation of this vital research initiative. Our sincere thanks go to the dedicated scientists, project personnel, and technical staff whose commitment has made this long-term study possible. We trust that the knowledge distilled in this bulletin will be of immense value to researchers, policymakers, students, and progressive farmers working toward a sustainable agricultural future.

Authors

1. Introduction

Modern agriculture faces several challenges, including soil degradation, biodiversity loss, water scarcity, low profitability, and food insecurity (Muluneh, 2021). These issues largely stem from unsustainable farming practices such as intensive tillage, overuse of chemical inputs, and monocropping. These methods threaten environmental integrity, ecosystem stability, and human well-being. Compounding the problem, climate change has introduced additional abiotic stresses that significantly affect natural resources, crop productivity, and global food security. In this context, sustaining food production without further environmental degradation becomes increasingly difficult, if not unfeasible amid ongoing population growth. Consequently, comprehensive and transformative strategies are essential to address these multifaceted challenges effectively. The Sustainable Development Goals (SDGs), endorsed by all member states of the United Nations, offer a comprehensive framework for addressing these issues, with a strong emphasis on sustainable agriculture as a cornerstone for food security and environmental protection (UN, 2015).

Conservation Agriculture (CA) has emerged as a promising and sustainable approach capable of addressing many of these pressing challenges by fostering ecosystem health, enhancing resilience, and supporting long-term agricultural productivity (Friedrich et al., 2012). The adoption of CA practices can mitigate soil erosion, improve nutrient cycling, and conserve water resources. These outcomes align with several SDGs, notably Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), and Life on Land (SDG 15) (Farooq, 2023). According to the Food and Agriculture Organization (FAO) of the United Nations, CA is characterized by three core principles: minimal soil disturbance, permanent soil cover, and diversification of crop species. This approach enhances biodiversity and supports natural biological processes above and below the soil surface, thereby improving water and nutrient use efficiency and ensuring stable crop yields over time. As a result, CA is vital for the future of sustainable agriculture. The 2019 IPCC report on *Climate Change and Land* highlights CA as a key strategy for adapting to climate-related risks. Its three foundational principles are 1. reduced tillage (limited to 20–25%), 2. crop diversification (through rotation and intercropping), and 3. residue retention (maintaining over 30% soil cover), play a pivotal role in protecting ecosystems, reducing greenhouse gas emissions, and advancing sustainable land management

Globally, CA is practiced on around 180 million hectares of cropland, which accounts for approximately 12.5% of the world's cultivated area. Its adoption is relatively balanced between the Global North and Global South. Over the past two decades, CA cropland has expanded at an average annual rate of 10.5 million hectares. The most extensive adoption has occurred in South and North America, followed by regions such as Australia and New Zealand, Asia, Russia and Ukraine, Europe, and Africa. In Asia, CA adoption is a more recent phenomenon. It has taken root both on large-scale farms, as seen in Kazakhstan and China, and on smaller holdings in India and Pakistan. In particular, the rice-wheat cropping systems of the Indo-Gangetic Plains are being adapted to CA through 'double no-till' methods. In some regions, short-duration legumes like mung bean have been successfully introduced into the cropping cycle (Kassam et al., 2020).

CA provides a wide range of benefits at multiple scales. At the nano level, it improves soil health; at the micro level, it reduces input use, increases farm income, and lowers production costs; and at the macro level, it contributes to food security, poverty reduction, and climate change mitigation. Despite these benefits, adoption among smallholder farmers in India has been relatively slow. Recognizing its transformative potential, the Indian Council of Agricultural Research (ICAR) launched the "Consortia Research Platform on Conservation Agriculture (CRP–CA)" in 2015–16, headquartered at the ICAR–Indian Institute of Soil Science (IISS), Bhopal.

2. Why CA in rice-wheat system in IGP

The rice–wheat cropping system (RWS), covering roughly 10.3 million hectares across the Indo-Gangetic Plain (IGP) of India, plays a critical role in national food security and sustains the livelihoods of millions (Chauhan et al., 2012). Although the region has traditionally maintained a balance between food grain production and consumption, it now faces increasing pressure due to rising food demand and diminishing arable land. In recent years, yields under conventional RWS practices have stagnated or declined (Bhatt et al., 2016). Common traditional methods, such as soil puddling for rice transplanting and open-field burning of crop residues, have contributed to a host of issues-deteriorating soil health, falling groundwater levels, environmental pollution, inefficient resource use, and reduced farm profitability (Chauhan et al., 2012). Practices such as intensive tillage and puddling in rice cultivation are not only water-intensive but also accelerate soil degradation. Moreover, rice transplanting through conventional means is labour-demanding and increasingly unsustainable amid labour shortages triggered by industrial growth. In wheat cultivation, repeated tillage delays sowing, subjecting the crop to terminal heat stress and ultimately decreasing yields. Research indicates that each day's delay in wheat sowing due to intensive land preparation can reduce yields by 35–60 kg per hectare (Pathak et al., 2003).

Residue burning, especially prevalent in northwestern India, has emerged as a major environmental concern. This practice is particularly detrimental during the winter months, when it significantly contributes to air pollution (Jain et al., 2014). The narrow interval-typically 10 to 15 days between rice harvest and wheat sowing under conventional systems often forces farmers to burn rice stubble to prepare fields in time. The development of the "Turbo Happy Seeder," however, has offered a breakthrough solution by enabling direct seeding of wheat into rice residues, thereby eliminating the need for burning (Sidhu et al., 2015). Adopting conservation tillage encompassing reduced or zero tillage alongside residue management through retention or incorporation presents a sustainable alternative to traditional practices. These approaches have demonstrated improvements in both the physical and chemical characteristics of soil. Zero tillage combined with the Turbo Happy Seeder not only reduces fuel and labour inputs but also facilitates effective residue recycling, significantly enhancing soil quality (Singh et al., 2022; Fagodiya et al., 2024a).

Conservation tillage also lowers fossil fuel consumption (Pratibha et al., 2015), which in turn reduces greenhouse gas emissions and the system's overall global warming potential. Incorporating crop residues helps regulate soil temperature and moisture while supporting carbon sequestration critical for long-term soil sustainability (Lal, 2013). However, to achieve yield potential equivalent to puddled transplanted rice, and the proliferation of weeds remains a key constraint in direct-seeded rice (DSR) systems (Singh et al., 2017; Fagodiya et al., 2024b). Ensuring long-term productivity in the RWS requires urgent efforts to reverse natural resource degradation. Additionally, rising input costs necessitate the development of technologies that improve input-use efficiency and farm profitability. Therefore, this study aims to enhance and sustain crop productivity, restore soil health, and improve economic returns through resource-efficient practices within the rice–wheat system.

3. Rationale of the project

Agriculture remains the backbone of the Indian economy, providing livelihoods for a majority of the population. Although the country has attained food self-sufficiency, several persistent challenges continue to threaten the sustainability of the agricultural sector. These include yield stagnation, inefficient use of water and nutrients, declining farm profitability, soil degradation, and increasing vulnerability to climate change. Meeting the food demands of a growing population, especially with a rising preference for resource-intensive diets, poses a significant challenge, particularly in the context of shrinking farmland. Addressing these issues requires the adoption of sustainable agricultural practices that can enhance productivity, improve farm incomes, conserve natural resources, and reduce environmental degradation. Conservation Agriculture (CA) presents a viable and promising strategy, and by optimizing input use, such as water and labour, minimizing environmental pollution, improving soil health, and strengthening resilience to climate variability, CA offers a pathway toward more sustainable and climate-resilient farming systems. However, the widespread benefits of CA have yet to be fully realized. This is partly due to its dependence on context-specific, knowledge-intensive approaches involving specialized equipment, suitable crop varieties, and effective pest and nutrient management practices. Over the past two decades, various institutions—including the Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs), the International Maize and Wheat Improvement Center (CIMMYT), and several NGOs have made considerable progress in developing and promoting CA. Nevertheless, further concerted efforts are necessary to achieve large-scale adoption. To this end, ICAR launched the "Consortia Research Platform on Conservation Agriculture" (CRP–CA) during 2015–2016, with the objective of integrating CA into mainstream agricultural practices. The platform focuses on the sustainable management of natural resources to enhance productivity and ensure long-term food security. As part of this initiative, a targeted project entitled "Productive Utilization of Salt-Affected Soils through Conservation Agriculture" was implemented at the ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, with the following objectives:

1. To refine the CA technologies to sustain the productivity of rice –wheat cropping systems through efficient use of water, nutrient and energy in partially reclaimed sodic soils.
2. To quantify the impact of resource conservation options on the physical, chemical and biological soil health.
3. To evaluate the economic feasibility of various resource conservation options.

The conceptual framework for the rationale behind conservation agriculture in is summarized in Fig. 1.

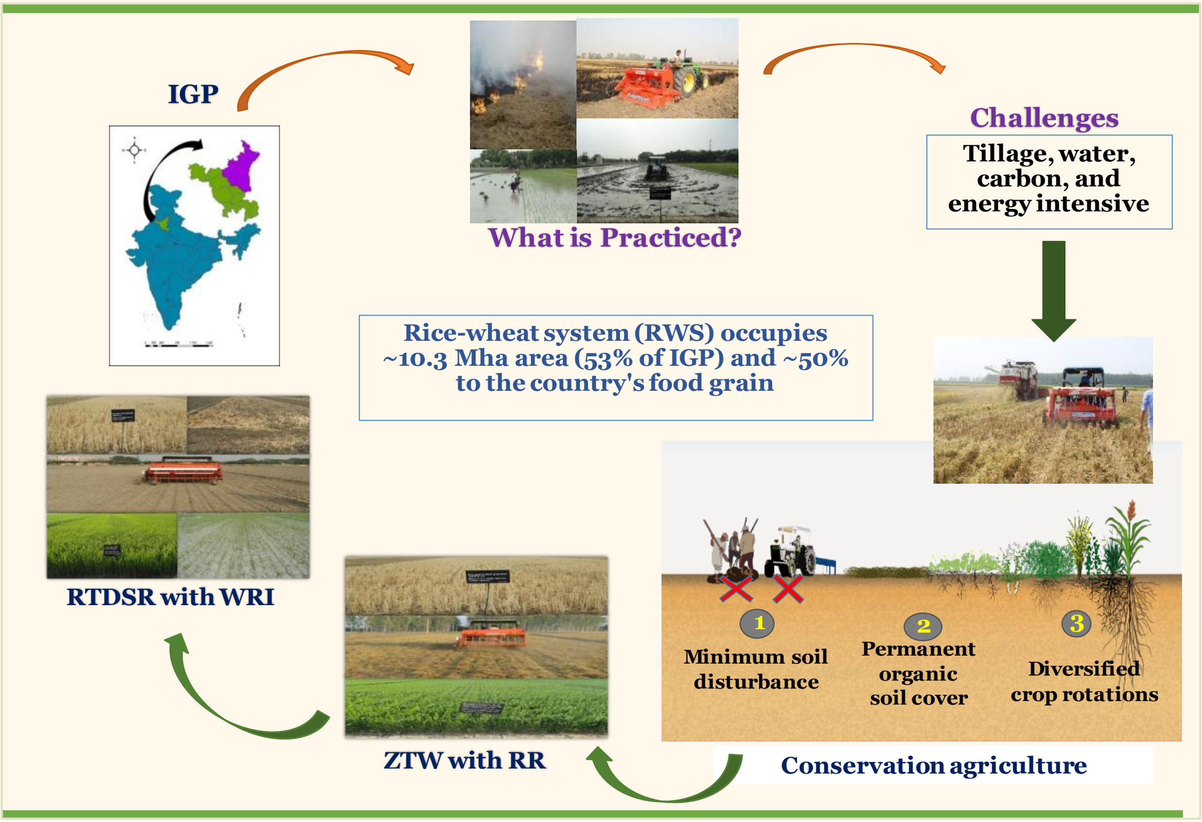


Fig. 1. Rationale behind conservation agriculture in rice-wheat system in Indo-Gangetic Plains of India

4. Experimental site, soil and climate

A 15-year long-term field experiment was initiated in 2006, at ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal (29°43′N, 76°58′ E, 244 m above mean sea level), Haryana, to examine the impact of resource conservation technologies (RCTs) (Tillage and residue management practices) in rice-wheat system. The location map of the study area and experimental site is presented in Fig. 2. and Fig. 3. The soil of the experimental site represents well drained reclaimed sodic soil (pH: 8.28 and EC: 0.32 dS m^{-1}) with sandy clay loam texture (59% sand, 18% silt and 23% clay), which was before reclamation classified as Typic Natrustlaf. The initial soil characteristics status of surface soil (0–15 cm) is presented in Table 1. The climate of the region is subtropical type with warm summer (April–September) and cold winter (October–

March). Long-term average precipitation in the area is 750 mm, of which nearly 80% is received during July–September coinciding with monsoon rains.

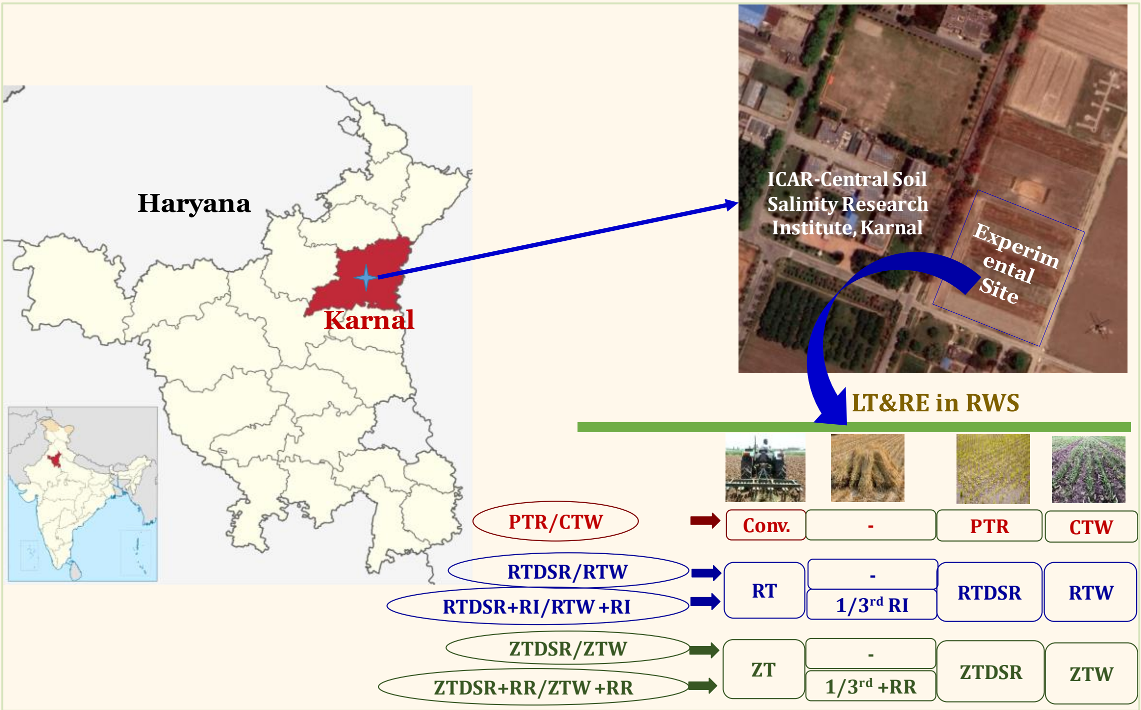


Fig. 2. Location map of tillage and residue management experiment at ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal.

Fig. 3. Aerial view of field experimental a) after rice harvest and b) wheat crop at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal.

Table 1. Initial soil properties of the experiment field of surface soil (0-15 cm).

Parameter	Values
Texture	Sandy clay loam Sand (59%), Silt (18%) and clay (23%)
$pH_{(1:2)}$	8.28
$EC_{(1:2)}$	0.32 dS m^{-1}
Organic Carbon (kg ha^{-1})	0.63 %
Available Nitrogen (kg ha^{-1})	117.6 kg ha^{-1}
Available Phosphorus (kg ha^{-1})	25.8 kg ha^{-1}
Available Potassium (kg ha^{-1})	260.5 kg ha^{-1}

5. Treatment combinations and crop management

The field experiment consisted of five treatment combinations of crop establishment, tillage, residue management popularly known as the scenarios (Sc) in RWS, as mentioned below:

1. **Sc-1**: Puddled transplanted rice (PTR) followed conventionally tilled wheat (CTW) or farmers' practice, abbreviated as PTR/CTW.
2. **Sc-2:** Reduced till direct seeded rice (RTDSR) followed reduced tilled wheat (RTW), abbreviated as RTDSR/RTW
3. **Sc-3:** RTDSR followed RTW with 1/3rd residue incorporation in both crops, abbreviated as RTDSR+RI/RTW+RI.
4. **Sc-4:** Zero tilled direct seeded rice (ZTDSR) followed zero tilled wheat (ZTW), abbreviated as ZTDSR/ZTW.
5. **Sc-5:** ZTDSR followed ZTW with 1/3rd residue retention/anchored in both crops, abbreviated as ZTDSR+RR/ZTW+RR.

5.1. Field preparation and residue management

- In Sc-1 (PTR/CTW), a sequence of tillage operations was performed to prepare a fine seedbed, while in reduced tillage DSR followed by reduced tillage wheat (Sc-2 and Sc-3) the soil was less disturbed due to the implementation of only 50% of the tillage operations conducted as Sc-1 (PTR/CTW). In zero tillage DSR followed by zero tillage wheat (Sc-4 and Sc-5), soil remained undisturbed, and no tillage operation was performed, only tillage necessary for sowing of seed was carried out.
- In RTDSR+RI/RTW+RI (Sc-3), approximately 1/3rd crop residue of previous crop was incorporated and sowing of succeeding crop was done. While in Sc-5 (ZTDSR+RR/ZTW+RR), approximately 1/3rd anchored crop residue was retained and sowing was subsequently carried out using Turbo Happy Seeder.
- Both the crops were harvested with the help of combined harvester at 1/3rd height and loose residue was removed manually. Remaining 1/3rd anchored residue was incorporated in Sc-3 and kept as anchored residue in Sc-5 for the uniform amount of residue retention and ease of field operation.
- The annual amount of crop residue added to soil was 4.89 and 4.42 Mg ha^{-1} yr^{-1} in Sc-3 (RTDSR+RI/RTW+RI), and Sc-5 (ZTDSR+RR/ZTW+RR), respectively. In Sc-1 (PTR/CTW), Sc-2 (RTDSR/RTW), and Sc-4 (ZTDSR/ZTW) crop residue was completely removed manually.
- Details regarding crop establishment, tillage intensity and residue management for rice and wheat crops are summarized in Table 2.

5.2. Crop establishment and seed rate

The rice crop was established during monsoon season (June-October). The crop was directly sown under reduced tillage (Sc-2 and Sc-3) and zero tillage (Sc-4 and Sc-5) using 25 kg seed ha^{-1} in first week of June. In Sc-1 (PTR), rice nursery was raised in the first fortnight of June using 10 kg seed ha^{-1}. Thereafter, transplanting of 30 days old seedlings was done at 15 cm × 15 cm hill spacing in well puddled and leveled field during first fortnight of July. Harvesting was done at physiological maturity in both PTR and DSR managed plots. Sowing of wheat was done using 100 kg seed ha^{-1} during mid-November and the crop was harvested in mid-April in all the scenarios.

5.3. Nutrient management

Both the crops were fertilized with 150:60:60 kg ha^{-1} of N (urea), P_2O_5 (di–ammonium phosphate) and K_2O (Muriate of Potash). P and K were applied as basal dose in both the crops. In conventional practice (Sc-1), 50 kg ha^{-1} N was applied at the time of transplanting and rest 100 kg ha^{-1} was top-dressed in 2 equal splits at 3 and 6 weeks after transplanting in rice and with first and second irrigation in wheat. In DSR (Sc-2 to Sc-4), 50 kg ha^{-1} N was applied at each 20, 40 and 60 days after sowing (DAS). Zinc sulphate ($ZnSO_4.7H_2O$) 25 kg ha^{-1} was also applied at sowing time in DSR. In addition, ferrous sulphate ($FeSO_4.7H_2O$) 7 kg ha^{-1} was top dressed in DSR at 40 DAS to counter iron deficiency.

5.4. Water management

Rice and wheat crops were surface irrigated in all five scenarios. Continuous submergence (5 cm) was maintained in PTR for initial 20 days of seedling establishment; thereafter, intermittent wetting and drying (IWD) conditions were retained during the vegetative growth, and again continuous ponding/submergence was managed from flowering to grain filling stage. In DSR (dry seeding followed by irrigation), first irrigation was applied within one day of seeding to ensure uniform germination and avoid seedling mortality. Follow up irrigations were applied with appearance of small cracks on soil surface. Irrigation was stopped 20 days before crop harvest. In wheat crop, 6 cm of irrigation was applied at critical phenological stages.

5.5. Weed management

In DSR, management of weeds was done though two sprays of herbicides and 1 manual weeding. Pendimethalin 30% EC (Stomp) @ 0.75 kg ha^{-1} as pre-emergence (PRE) was applied within 2 DAS followed by bispyribac–sodium 10% SC (Nominee Gold) @ 0.025 kg ha^{-1} as post-emergence (POST) at 25 DAS. Given quantities of herbicides were dissolved in 500-liters of water and sprayed using battery operated knapsack sprayer. One manual weeding for left over weeds was done at 35 DAS. In PTR, pretilachlor 37% EW (Rifit Plus) @ 1.0 kg ha^{-1} PRE 3 days after transplanting (DAT) was sprayed for broad spectrum weed control. In wheat, pendimethalin 30% EC (Stomp) @ 1.5 kg ha^{-1} PRE followed by pinoxaden 5.1% EC (Axial) 0.05 kg ha^{-1} POST 20-25 DAS was sprayed uniformly in all the treatment plots for effective weed management.

Table 2: Detail description of the crop management practices for rice and wheat crops under different scenarios of tillage and residue management.

Management practice	Sc-1: PTR/CTW (Farmers' practice)	Sc-2: RTDSR/RTW	Sc-3: RTDSR+RI/ RTW +RI	Sc-4: ZTDSR/ ZTW	Sc-5: ZTDSR+RR/ ZTW +RR
Field preparation	Rice: Two passes of disc and puddle harrow, one planking; Wheat: Two passes of disc harrow and cultivator each, one planking	Rice: One pass disc harrow and cultivator, one planking; Wheat: One pass of disc harrow and cultivator, one planking	Same as Sc-2	No tillage	Same as Sc-4
Residue management	100% residue removal	Same as Sc-1	1/3rd residue incorporation	Same as Sc-1	1/3rd residue retention
Seed rate	Rice: 10 kg ha^{-1} (nursery raising); Wheat: 100 kg ha^{-1}	DSR sowing: 25 kg ha^{-1} Wheat: 100 kg ha^{-1}	Same as Sc-2	Same as Sc-2	Same as Sc-2
Fertilizer dose (N:P:K)	Rice: 150:60:60 kg ha^{-1} Wheat:150:60:60 kg ha^{-1}	Rice: 150:60:60 kg ha^{-1}+ 25 kg $ZnSO_4$ ha^{-1} + 7 kg $FeSO_4$ ha^{-1}; Wheat: 150:60:60 kg ha^{-1}	Same as Sc-2	Same as Sc-2	Same as Sc-2
Water management	Rice: Continuous submergence for initial 30 days, thereafter irrigation at 2 days after disappearance of ponded water; Wheat: Irrigation at critical growth stage	Rice: Field was kept moist for initial 15 days and then irrigation based on appearance of small cracks Wheat: Irrigation at critical growth stage	Same as Sc-2	Same as Sc-2	Same as Sc-2
Weed management	Rice: Pretilachlor 37% EW (Rifit Plus) @ 1.0 kg ha^{-1} PRE*; Wheat: Pendimethalin 30% EC (Stomp) 0.75 kg ha^{-1} PRE followed by pinoxaden 5.1% EC (Axial) 0.05 kg ha^{-1} POST**	Rice- Pendimethalin 30% EC (Stomp) 0.75 kg ha^{-1} PRE followed by bispyribac-sodium 10% SC (Nominee Gold) 0.025 kg ha^{-1} POST; Wheat- Pendimethalin 30% EC (Stomp) @ 1.5 kg ha^{-1} PRE followed by pinoxaden 5.1% EC (Axial) 0.05 kg ha^{-1} POST	Same as Sc-2	Same as Sc-2	Same as Sc-2

*PRE: Pre-emergence (within 2 days after sowing, DAS/transplanting in rice and wheat); **POST: Post-emergence (20–25 DAS in DSR and 30 DAS in wheat)

6. Major research achievements

6.1. Crop productivity

Temporal yield trends

- The temporal yield trends of rice and wheat since start of the experiment (2006-07) are presented in Fig. 4a and 4b.
- Rice varieties grown during the experimental period were salt-tolerant Basmati CSR-30 (2006 and 2007), Pusa-44 (2008 and 2009), hybrid rice Arize-6129 (2010–2016, 2018 and 2021–2023), salt-tolerant CSR-43 (2017), and salt-tolerant CSR-46 (2019 and 2020).
- Wheat varieties grown during the experimental period were PBW-343 (2006–07, 2007–08 and 2008–09), DBW-17 (2009–10, 2010–11 and 2011–12), HD-2967 (2012–13 to 2019–20) and DBW-222 (2020–21 to 2022–23) KRL-210 (2023–24).
- Temporal trend showed that rice yield exhibited considerable inter-annual variability across different tillage and establishment methods, largely influenced by varietal changes and climatic factors.
- While PTR showed early yield gains, reduced and zero tillage DSR systems demonstrated more stable or improving performance over time, particularly with reduced tillage DSR showing consistent yields from 2013 to 2018.
- The sharp yield decline observed in 2020 under zero tillage DSR highlights the sensitivity of these systems to adverse conditions, although recovery in 2021 suggests resilience with appropriate management.
- Wheat grain yield showed an overall increasing trend until 2011–12, with the highest yield recorded that year, followed by a period of relative stability from 2015–16 to 2020–21.
- Significant yield fluctuations in certain years, including the sharp decline in 2023–24, were primarily driven by varietal changes, weather variability, and differences in soil health and management practices.
- The combined influence of variety selection, climate, and agronomic management practices played a key role in determining year-to-year variations in both rice and wheat yields.

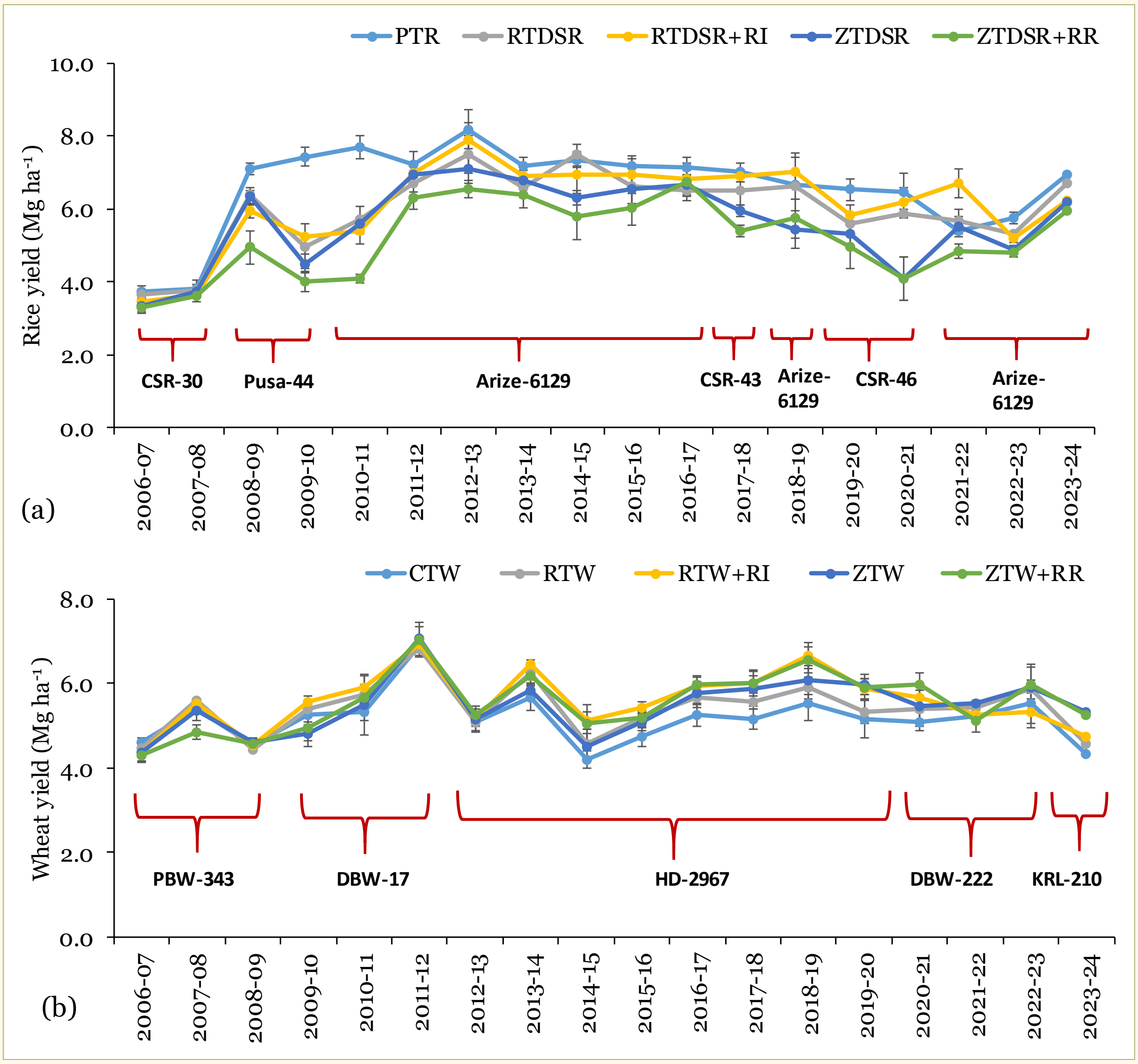


Fig. 4. Trends in grain yield of (a) rice and (b) wheat during 15-year of the experimentation under tillage and residue management in rice-wheat system.

Average crop yield

The fifteen-year average yield and sustainable yield index of rice, wheat, and RWS is presented in Table 3.

Rice Yield

- Significant variations in rice yield were reported in various scenarios of crop establishment methods, tillage and residue practices.
- The highest 15-year pooled average rice yield (6.73 Mg ha^{-1}) was recorded under Sc-1 (PTR), followed by Sc-3 (RTDSR + residue incorporation) at 6.14 Mg ha^{-1}, and lowest (5.28 Mg ha^{-1}) was observed in Sc-5 (ZTDSR + anchored residue).

- There was a reduction of rice yield in all the scenarios of DSR compared to PTR, however the reduction was more in zero tillage DSR compared to reduced tillage DSR.
- Yield trends over time showed the highest annual increase in Sc-3 (0.21 Mg ha^{-1} yr^{-1}), indicating long-term yield improvement potential under RTDSR with residue incorporation.
- Sc-1 (PTR) was the most sustainable (SYI = 0.65), followed by RTDSR (Sc-3; 0.58), while Sc-5 (ZTDSR+RR) was the least sustainable (SYI = 0.50).

Wheat Yield

- Sc-3 (RTW) achieved the highest wheat yield (5.68 Mg ha^{-1}), a 9.2% increase over conventional till wheat (CTW).
- Sc-5 (ZTW) also showed a notable improvement (5.54 Mg ha^{-1}), 6.5% higher than CTW.
- All the scenarios of reduced and zero tillage wheat had higher SYI, and Sc-3 (RTW) had the highest sustainability (SYI = 0.69).
- Long-term yield trends showed the highest increase in Sc-5 (0.12 Mg ha^{-1} yr^{-1}), indicating better adaptability under zero-tillage wheat with residues.

Table 3. 15-year pooled average yield and sustainable yield index of rice, wheat and rice-wheat system in various scenarios

Scenarios/ treatments	Grain yield (Mg ha^{-1}) 15-year pooled mean			Sustainable yield index (SYI)		
	Rice	Wheat	RWS	Rice	Wheat	RWS
Sc-1	6.73^{a}	5.20^{c}	11.93^{a}	0.65^{a}	0.64^{e}	0.73^{a}
Sc-2	6.05^{b}	5.43^{b}	11.48^{b}	0.58^{b}	0.67^{b}	0.70^{b}
Sc-3	6.14^{b}	5.68^{a}	11.82^{a}	0.58^{c}	0.69^{a}	0.70^{b}
Sc-4	5.76^{c}	5.43^{b}	11.18^{b}	0.55^{d}	0.65^{d}	0.67^{c}
Sc-5	5.28^{d}	5.54^{b}	10.82^{c}	0.50^{e}	0.66^{c}	0.63^{d}
p-Value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Note: Means with the same letter in a column are not significantly different at 5 % level of significance using DMRT. *Treatments effect was found to be non-significant.

Rice-wheat system Yield

- Overall, on a system basis, the highest system yield (11.93 Mg ha^{-1}) was found in Sc-1 (PTR/CTW), closely followed by Sc-3 (11.82 Mg ha^{-1}).
- All scenarios showed positive yield trends over time, with Sc-3 and Sc-5 demonstrating the highest annual improvements (0.29 and 0.28 Mg ha^{-1} yr^{-1}, respectively).
- Yield improvement in these conservation-based scenarios was nearly double that of Sc-1 (0.14 Mg ha^{-1} yr^{-1}). This highlights the growing advantage of conservation agriculture practices in sustaining long-term productivity.

- Sc-1 (PTR/CTW) had the highest SYI (0.73), followed by Sc-2 = Sc-3 > Sc-4 > Sc-5, indicating a decline in sustainability with increasing intensification without proper management.

6.2. *System profitability*

The 15-year average cultivation cost, gross return, return over variable cost (net return) and benefit cost ratio (BCR) of the rice, wheat and RWS is given in Table 4.

Rice economics

- The highest cost of rice cultivation was recorded in the PTR (₹52,068/ha), while the lowest was in the ZTDSR system (₹44,163/ha).
- Although the non-significant benefit-cost ratio (BCR), the highest BCR was observed in reduced tillage DSR with residue incorporation (Sc-3; 2.45), followed closely by Zero tillage DSR (Sc-4; 2.43) and PTR (Sc-1; 2.42).
- Zero tillage DSR with residue retention (Sc-5) was the least profitable system, yielding the lowest gross return, net profit, and BCR of 2.11.
- All rice cultivation treatments showed a BCR greater than 1.0, indicating they are economically viable.

Wheat economics

- The highest cost of cultivation was observed in CTW (₹31,706/ha), while the lowest was in ZTW (₹24,986/ha).
- RTW, RTW+RI, and ZTW recorded statistically similar gross returns, with CTW showing the lowest RTW the highest.
- ZTW was the most profitable system, with the highest gross return (₹120,760/ha), net profit (₹95,774/ha), and benefit-cost ratio (BCR) of 4.83.
- CTW showed the lowest profitability with a BCR of 3.65 and net profit of ₹83,990/ha.

Rice-wheat system economics

- Compared to Sc-1 i.e., PTR/CTW (₹83,773/ha), all other treatments showed a 10.9% to 17.4% reduction in cultivation costs, with ZTDSR/ZTW having the lowest at ₹69,148.5/ha.
- The maximum gross return (₹2,41,476/ha) was recorded under PTR/CTW, where rice contributed 62.2% and wheat 37.8%.
- Despite the highest gross return, PTR/CTW had lower net profit due to its high cost of cultivation, making it less economically efficient compared to Sc-2 and Sc-3.
- Overall Sc-3 (RTDSR+RI/ZTW+RI) emerged as the most profitable RWS treatment, combining the comparatively lower cultivation cost (₹7,45,88/ha) with high net profit (₹1,60,601/ha) and BCR (3.15).

Table 4. 15-year average cost of cultivation, net return and benefit cost ratio of rice, wheat and rice-wheat system in various scenarios.

Crop	Treatments/ scenarios	Cost of cultivation (Rs. ha^{-1})	Gross return (Rs. ha^{-1})	Net return (Rs. ha^{-1})	BCR
Rice	PTR/CTW	52068^{a}	125780^{a}	73712^{a}	2.42^{a}
	RTDSR/RTW	46883^{b}	113004^{b}	66121^{b}	2.41^{a}
	RTDSR+RI/RTW+RI	46883^{b}	114692^{b}	67809^{b}	2.45^{a}
	ZTDSR/ZTW	44163^{c}	107527^{c}	63364^{b}	2.43^{a}
	ZTDSR+RR/ZTW+RR	46663^{b}	98677^{d}	52015^{c}	2.11^{b}
Wheat	PTR/CTW	31706^{a}	115696^{b}	83990^{d}	3.65^{c}
	RTDSR/RTW	27706^{b}	120770^{a}	93064^{b}	4.36^{b}
	RTDSR+RI/RTW+RI	27706^{b}	120499^{a}	92793^{b}	4.35^{b}
	ZTDSR/ZTW	24986^{c}	120760^{a}	95774^{a}	4.83^{a}
	ZTDSR+RR/ZTW+RR	27486^{b}	117569^{b}	90083^{c}	4.28^{b}
RWS	PTR/CTW	83773^{a}	241476^{a}	157702^{a}	2.88^{c}
	RTDSR/RTW	74588^{b}	233774^{b}	159185^{a}	3.13^{b}
	RTDSR+RI/RTW+RI	74588^{b}	235191^{b}	160603^{a}	3.15^{b}
	ZTDSR/ZTW	69148^{d}	228287^{c}	159138^{a}	3.30^{a}
	ZTDSR+RR/ZTW+RR	74148^{c}	216246^{d}	142097^{b}	2.91^{c}

Note: Means with the same letter in a column are not significantly different at 5% level of significance using DMRT. The input and output are the average values from year 2006-07 to 2023-24. The gross return and costs were estimated using the prevailing prices of the year 2023-24.

6.3. *Soil health assessment*

6.3.1. *Soil physical properties*

- The assessment of soil health after the completion of 15-year of the experimentation was done and results are presented in Table 5.
- Surface soil bulk density (BD): Various scenarios of tillage, residue and crop establishment practices significantly affected BD in the 0–15 cm soil layer, with the lowest BD observed under Sc-5 (ZTDSR+RR/ZTW+RR), which was 5% lower than the highest (1.53 Mg/m^3) BD in Sc-1 (PTR/CTW).
- Subsurface soil bulk density: In the 15–30 cm soil layer, BD values (1.64–1.67 Mg/m^3) were consistently higher than surface soil but showed no significant differences among the treatments.
- Soil Penetration Resistance (SPR): SPR was greatly affected by various practices across the full 0–45 cm profile, and variations were observed with depth (Fig. 5). At 0–15 cm depth, SPR was moderately higher in PTR/CTW (sc-1) compared zero

tillage scenarios, with a sharp increase below 15 cm, peaking at 22.5 cm in PTR/CTW, before declining with depth.

- The lowest SPR was recorded in Sc-5 (ZTDSR+RR/ZTW+RR), showing a 22.3% and 30.9% reduction compared to PTR/CTW in overall and 15–30 cm depths, respectively.
- Infiltration rate (IR): Infiltration rate was significantly higher in Sc-5 (ZTDSR+RR/ZTW+RR; 7.8 mm/h) and lowest under Sc-1 (PTR/CTW; (3.0 mm/h)
- Infiltration Time Trend: All treatments showed the highest infiltration in the first 5 minutes (due to macropores and air release), then a sharp decline till 90 minutes, and a stable phase from 180 to 330 minutes (Fig. 6).
- Cumulative infiltration rate (CIR) rose steeply in the first 90 minutes, followed by gradual increase and stabilization after 210 minutes; zero tillage treatments showed the highest CIR, while PTR/CTW had the lowest.
- Overall long-term zero tillage combined with residue retention significantly improves soil health by lowering BD, reducing SPR, and increasing infiltration capacity making it superior to conventional practices.

Table 5. Soil physical properties in various scenarios after 15-year of experimentation.

Treatments/ scenarios	Bulk density ($Mg\ m^{-3}$)	Soil penetration resistance (KPa)	Infiltration rate ($mm\ h^{-1}$)
0-15 cm soil layer			
PTR/CTW	1.53^{a}	1681.91	3.00^{e}
RTDSR/RTW	1.52^{a}	1529.45	4.70^{d}
RTDSR+RI/RTW+RI	1.50^{ab}	1550.82	5.80^{c}
ZTDSR/ZTW	1.47^{bc}	1591.23	6.50^{b}
ZTDSR+RR/ZTW+RR	1.45^{c}	1306.02	7.80^{a}
Significance	**	NS	***
15-30 cm soil layer			
PTR/CTW	1.67	2985.11^{a}	
RTDSR/RTW	1.65	2373.09^{abc}	
RTDSR+RI/RTW+RI	1.64	2156.91^{bc}	
ZTDSR/ZTW	1.65	2211.86^{bc}	
ZTDSR+RR/ZTW+RR	1.66	2060.86^{c}	
Significance	NS	*	

Treatment means within a column with dissimilar letters (lowercase) varied significantly ($p < 0.05$, Tukey's test). ***, **, * represents 0.1% (0.001), 1% (0.01), and 5% (0.05) level of significance, and NS represent non-significant.

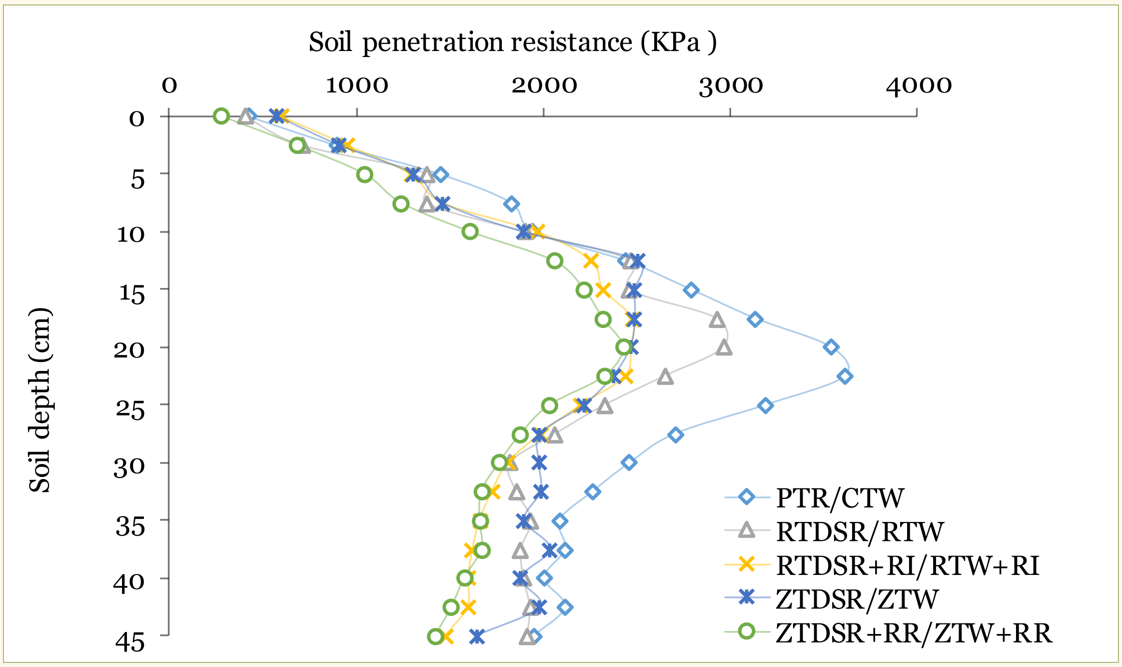


Fig. 5. Soil penetration resistance in various scenarios after 15-year of experimentation.

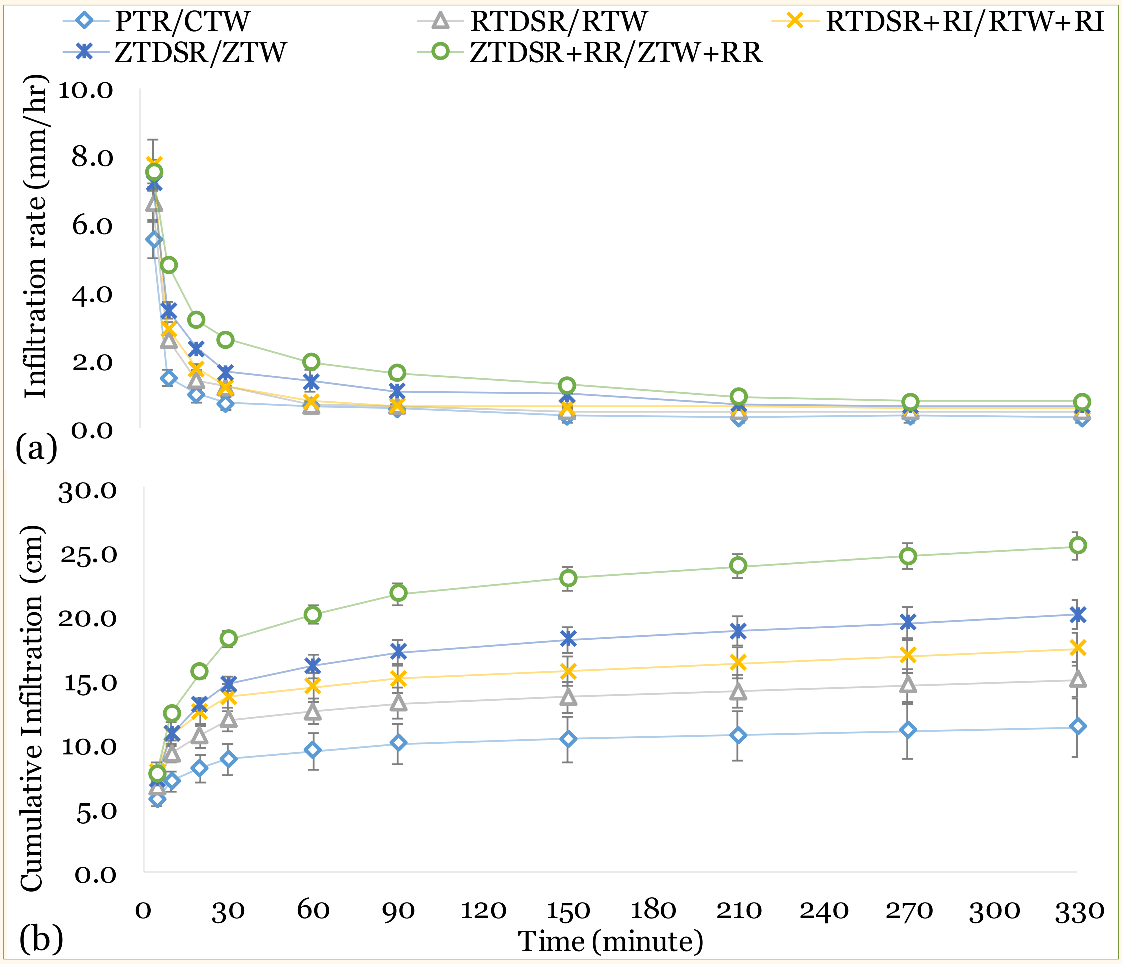


Fig. 6. Soil infiltration (a) infiltration rate, and (b) cumulative infiltration as influenced by various scenarios after 15-year of experimentation.

6.3.2. Soil chemical properties

The results of the soil pH, electrical conductivity, soil organic carbon, SOC stock at 0-15 and 15-30 cm soil layers after completion of 15-year of experimentation is presented in Table 6.

Soil pH and electrical conductivity (EC)

- No significant differences in soil pH and EC were observed across treatments at both soil depths (0–15 cm and 15–30 cm). However, a slightly higher pH and lower EC were recorded in the subsurface soil (15–30 cm) compared to surface soil (0–15 cm), indicating minimal vertical variation in basic soil chemical properties.

Soil organic carbon (SOC) and total organic carbon (TOC)

- Various scenarios of tillage, crop establishment, and residue management practices had a significant impact on SOC and TOC at both depths.
- Surface soil (0–15 cm) consistently exhibited higher SOC and TOC compared to the subsurface (15–30 cm).
- SOC increased by 20.50–30.43% at 0–15 cm, and 12.41–21.90% at 15–30 cm under various scenarios (Sc-2 to Sc-5) compared to conventional rice-wheat system practice (Sc-1; PTR/CTW).
- Similarly, TOC increased by 15.9-34.9% and ranged 7.87-10.59 g kg^{-1} under various scenarios (Sc-2 to Sc-5) at 0–15 cm, and 10.89-35.64% at 15–30 cm, in various scenarios (Sc-2 to Sc-5) compared Sc-1 (PTR/CTW).

SOC and TOC Stock

- SOC stock showed significant differences across various scenarios at both depths. At 0–15 cm, SOC stock ranged 13.74–16.77 Mg ha^{-1}, with 11.41–17.28% increase in various scenarios (Sc2-Sc-5) over PTR/CTW (Sc-1). At 15–30 cm, SOC stock was lower than surface soil, showing vertical decline with depth.
- ZTDSR+RR/ZTW+RR recorded the highest TOC stock at both soil depths, highlighting it as the most effective management practice for enhancing long-term soil carbon storage.

Table 6. Soil chemical properties in various scenarios as influenced by 15-year of experimentation.

Treatments/ scenarios	$pH_{1:2}$	$EC_{1:2}$ (dS m^{-1})	SOC (g kg^{-1})	TOC (g kg^{-1})	Stock (Mg ha^{-1})	
					SOC	TOC
0-15 cm soil layer						
PTR/CTW	7.53	0.27	5.96^{d}	7.87^{d}	13.74^{b}	18.12^{c}
RTDSR/RTW	7.50	0.25	7.19^{c}	9.12^{c}	16.30^{a}	20.69^{b}
RTDSR+RI/RTW+RI	7.52	0.28	7.30^{bc}	9.71^{b}	16.35^{a}	21.75^{b}
ZTDSR/ZTW	7.52	0.24	7.48^{b}	9.93^{b}	16.38^{a}	21.74^{b}
ZTDSR+RR/ZTW+RR	7.52	0.23	7.78^{a}	10.59^{a}	16.77^{a}	22.83^{a}
Significance	NS	NS	***	***	***	***
15-30 cm soil layer						
PTR/CTW	7.96	0.21	5.07^{d}	7.43^{d}	12.69^{c}	18.58^{d}
RTDSR/RTW	7.84	0.20	5.70^{c}	8.24^{c}	14.14^{b}	20.42^{c}
RTDSR+RI/RTW+RI	7.81	0.24	6.00^{ab}	9.04^{b}	14.74^{a}	22.22^{b}
ZTDSR/ZTW	7.98	0.20	5.89^{bc}	9.49^{ab}	14.42^{ab}	23.23^{ab}
ZTDSR+RR/ZTW+RR	7.88	0.19	6.19^{a}	10.07^{a}	14.89^{a}	24.25^{a}
Significance	NS	NS	***	***	***	***

Treatment means within a column with dissimilar letters (lowercase) varied significantly ($p < 0.05$, Tukey's test). ***, **, * represent 0.1% (0.001), 1% (0.01), and 5% (0.05) level of significance, and NS represent non-significant.

Dynamics of carbon pools

- The various management practices (Sc-2 to Sc-5) increased both active carbon pools (very labile and labile) and passive pools (less labile and non-labile) at 0-15 cm soil layer as compared to PTR/CTW. However, increase was more in active pools compared to both the soil layer. (Fig. 7)
- The active carbon pool increased by 28% in reduced tillage (Sc-2 and Sc-3), and by 36% under zero tillage scenarios (Sc-4 and Sc-5). However, passive pool increased by 10% in reduced tillage (Sc-2 and Sc-3), and by 23% under zero tillage scenarios (Sc-4 and Sc-5).
- This indicates that conservation tillage practices not only boost labile (active) carbon but also enhance the accumulation of stable (passive) carbon pools.
- In the subsurface soil (15–30 cm) as compared to surface soil (0–15 cm), decline was observed in active fractions. Very labile carbon decreased by 28%, Labile carbon decreased by 12%, and less labile carbon decreased by 10%. However, non-labile carbon (NL) increased by 34%, indicating more stable carbon accumulation in deeper layers.
- The active carbon pool constitutes more than 50% of total soil organic carbon, making it highly vulnerable to loss through decomposition. The passive carbon pool, although smaller in proportion, showed a 26% increase with improved

tillage and residue management compared to conventional tillage (PTR/CTW). Enhancing the passive pool is crucial for long-term carbon sequestration and soil carbon stability.

- Conservation agriculture practices, especially zero tillage and residue retention, effectively increase both active and passive carbon pools, improving soil carbon sequestration. While active carbon contributes to short-term nutrient cycling, increasing the passive pool helps build stable soil carbon stocks critical for climate change mitigation.

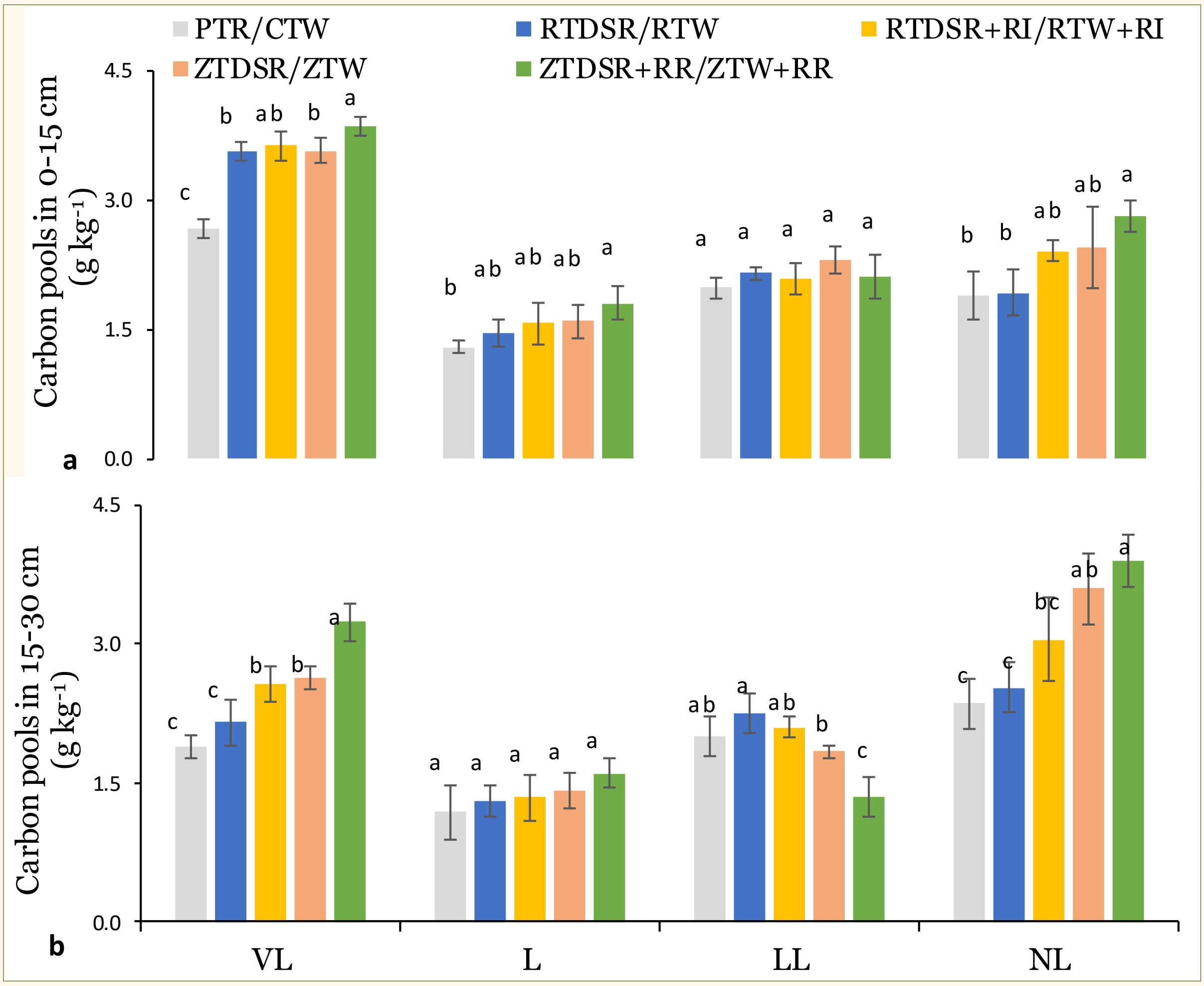


Fig. 7. Influence of various scenarios after 15-year of experimentation on carbon pools at (a) 0-15 cm and (b) 15-30 cm soil depth in rice-wheat system.

Plant available nutrients

- The various management practices (Sc-2 to Sc-5) increase the plant available nutrient particularly at 0-15 cm soil layer as compared to the PTR/CTW (Sc-1) (Table 7)
- ZTDSR+RR/ZTW+RR system showed the highest available N among various scenarios which is 25.1% higher in surface soil (0–15 cm) 4.1% higher in subsurface soil (15–30 cm) than PTR/CTW, indicates that zero tillage with

residue retention enhances N retention and availability, particularly in surface layers.

- Available phosphorus varied 23.93–34.07 kg ha^{-1} in various scenarios at 0–15 cm. RTDSR+RI/RTW+RI treatment recorded maximum P which is 23.8% increase in surface soil and 17.7% increase in subsurface soil compared to PTR/CTW. Suggests reduced tillage with residue incorporation aids in P availability, likely due to better organic matter decomposition and microbial activity.
- Available potassium varied 236.53–271.45 kg ha^{-1} at 0-15 cm soil layer in various scenarios. ZTDSR+RR/ZTW+RR consistently showed highest K availability which is 14.6% increase in surface soil and 11.0% increase in subsurface soil over PTR/CTW reflecting the positive role of residue recycling in maintaining soil K reserves.
- Zero tillage with residue retention (ZTDSR+RR/ZTW+RR) consistently enhanced the availability of macronutrients (N, K) and micronutrients (Zn, Fe). Reduced tillage with residue incorporation (RTDSR+RI/RTW+RI) was particularly beneficial for phosphorus availability. These findings underscore the positive role of conservation agriculture in improving soil nutrient status for sustainable productivity.

Table 7. Soil available macronutrients in various scenarios as influenced by 15-year of experimentation.

Treatments/ scenarios	Available macronutrient (kg ha^{-1})		
	Nitrogen	Phosphorus	Potassium
0-15 cm soil layer			
PTR/CTW	104.76^{d}	23.93^{d}	236.88^{c}
RTDSR/RTW	112.59^{c}	28.97^{b}	236.53^{c}
RTDSR+RI/RTW+RI	119.99^{b}	34.07^{a}	243.76^{c}
ZTDSR/ZTW	110.41^{c}	27.01^{c}	252.68^{b}
ZTDSR+RR/ZTW+RR	131.04^{a}	33.42^{a}	271.45^{a}
Significance	***	***	***
15-30 cm soil layer			
PTR/CTW	9288^{b}	2108^{b}	237.39^{c}
RTDSR/RTW	93.83^{b}	21.13^{b}	242.37^{bc}
RTDSR+RI/RTW+RI	100.00^{a}	26.10^{a}	247.89^{ab}
ZTDSR/ZTW	96.89^{ab}	22.43^{b}	242.38^{bc}
ZTDSR+RR/ZTW+RR	102.71^{a}	23.40^{b}	250.93^{a}
Significance	*	***	**

Treatment means within a column with dissimilar letters (lowercase) varied significantly ($p < 0.05$, Tukey's test) ***, **, * represent 0.1% (0.001), 1% (0.01), and 5% (0.05) level of significance, and NS represent non-significant.

6.3.3. Soil biological properties

- Microbial biomass carbon (MBC), a highly sensitive indicator of soil biological activity and organic matter turnover. Dehydrogenase activity (DHA), a marker of overall microbial oxidative activity and soil respiration. Alkaline phosphatase (ALP) activity reflects the phosphorus cycling and organic matter mineralization. These three microbial parameters are most important for soil biological health.
- Zero tillage + residue retention (ZTDSR+RR/ZTW+RR) recorded the highest values of the MBC, DHA, and ALP particularly in surface soil (Table 8). However, lowest values were observed in PTR/CTW, confirming the positive role of conservation tillage and residues in enhancing microbial activities.
- The trend observed for microbial parameters was observed as zero tillage followed by reduced tillage and conventional tillage. However, at subsurface (15–30 cm), zero tillage and reduce tillage differences became non-significant, showing deeper soil is less responsive to tillage effects.
- Zero tillage with residue retention (ZTDSR+RR/ZTW+RR) maximized soil microbial biomass and enzymatic activities, supporting better microbial functioning and nutrient cycling. Adoption of conservation agriculture (especially zero tillage with residues) plays a critical role in enhancing soil health, microbial activity, and long-term sustainability.

Table 8. Soil biological properties in various scenarios as influenced by 15-year of experimentation.

Treatments/scenarios	Microbial biomass carbon (mg kg^{-1} soil)	Alkaline phosphatase (µmol p-nitrophenol g^{-1} h^{-1})	Dehydrogenase activity (µg TPF g^{-1} 24 h^{-1})
0-15 cm soil layer			
PTR/CTW	135.50[e]	110.73[e]	76.36[e]
RTDSR/RTW	176.88[c]	140.63[d]	91.47[d]
RTDSR+RI/RTW+RI	254.00[b]	172.73[b]	104.85[b]
ZTDSR/ZTW	248.50[b]	158.30[c]	99.29[c]
ZTDSR+RR/ZTW+RR	271.63[a]	187.08[a]	122.00[a]
Significance	***	***	***
15-30 cm soil layer			
PTR/CTW	109.90[c]	90.94[e]	66.95[e]
RTDSR/RTW	172.93[a]	117.70[d]	74.54[d]
RTDSR+RI/RTW+RI	182.49[a]	142.82[b]	86.88[b]
ZTDSR/ZTW	174.41[a]	129.02[c]	80.93[c]
ZTDSR+RR/ZTW+RR	186.56[a]	151.56[a]	100.12[a]

6.4. GHG mitigation and carbon sequestration

The greenhouse gas (GHG) emissions, carbon sequestration potential, carbon footprint varied significantly among the various treatment scenarios (Table 9) different crop establishment and residue management scenarios.

- Total GHG emissions were highest under PTR/CTW at (11172.60 kg CO_2 eq ha^{-1}). The lowest emissions were observed under ZTDSR/ZTW at 6507.86 kg CO_2 eq ha^{-1}.
- Methane emissions were significantly higher in PTR/CTW (742.56 kg CO_2 eq ha^{-1}), reflecting its flooded conditions conducive to methanogenesis, whereas other treatments (dry/direct seeded systems) showed negligible methane emissions.
- Fuel consumption was significantly reduced in conservation agriculture-based practices. The lowest diesel-related emissions were recorded in ZTDSR/ZTW and ZTDSR+RR/ZTW+RR, compared to 518.10 kg CO_2 eq ha^{-1} in PTR/CTW.
- N_2O emissions were significantly lower in PTR/CTW (3787.04 kg CO_2 eq ha^{-1}) compared to the higher emissions in RTDSR+RI/RTW+RI (4238.08 kg CO_2 eq ha^{-1}) and ZTDSR+RR/ZTW+RR (4205.49 kg CO_2 eq ha^{-1}).
- Carbon sequestration potential (CSP) was highest in ZTDSR+RR/ZTW+RR at (5354.24 kg CO_2 eq ha^{-1} yr^{-1}), followed by ZTDSR/ZTW (4711.69 kg CO_2 eq ha^{-1} yr^{-1}) and RTDSR+RI/RTW+RI (4483.86 kg CO_2 eq ha^{-1} yr^{-1}).
- Net GHG emissions (total GHG emissions minus CSP) were significantly higher in PTR/CTW (8303.73 kg CO_2 eq ha^{-1}), whereas ZTDSR+RR/ZTW+RR had the lowest net emissions (1322.70 kg CO_2 eq ha^{-1}), indicating its strong potential as a climate-smart practice.
- Carbon footprint (kg CO_2 Mg^{-1} of grain yield) was highest under PTR/CTW (703.93 kg CO_2 Mg^{-1}) and lowest under ZTDSR+RR/ZTW+RR (123.36 kg CO_2 Mg^{-1}), indicating a significant advantage of zero-tillage and residue retention in improving environmental efficiency per unit of production.

Table 9. Greenhouse gas emission, carbon sequestration, and carbon footprints in rice-wheat system (data pooled-averaged for 15-year).

Treatments /scenarios	GHG emission (kg CO_2 eq ha^{-1})								Carbon sequestration potential (kg CO_2 eq ha^{-1} yr^{-1})	Net GHG emission[#]	Carbon footprint[$] (kg CO_2 Mg^{-1})
	Diesel	Total N_2O	Methane	Herbicide	Irrigation Water	Seeds	Residue burning	Total GHG emission			
PTR/CTW	518.10^{a}	3787.04^{d}	742.56	21.95^{c}	2639.27^{a}	76.50^{b}	3387.20	11172.60^{a}	2868.89^{d}	8303.73^{a}	703.93^{a}
RTDSR/RTW	387.04^{b}	4091.87^{c}	-	28.30^{b}	2079.27^{c}	85.00^{a}	-	6671.49^{bc}	3876.65^{c}	2794.84^{b}	244.57^{b}
RTDSR+RI/ RTW+RI	387.04^{b}	4238.08^{a}	-	28.30^{b}	2094.95^{c}	85.00^{a}	-	6833.38^{b}	4483.86^{b}	2349.51^{b}	199.97^{c}
ZTDSR/ZTW	178.39^{c}	4086.40^{c}	-	51.40^{a}	2106.67^{bc}	85.00^{a}	-	6507.86^{c}	4711.69^{b}	1796.18^{c}	163.78^{cd}
ZTDSR+RR/ ZTW+RR	178.39^{c}	4205.49^{b}	-	51.40^{a}	2156.68^{b}	85.00^{a}	-	6676.95^{bc}	5354.24^{a}	1322.70^{c}	123.36^{d}
Treatments	***	***		***	***	NS		***	***	***	***

[#]Net GHG emission is the difference of total annual GHG emission and annual carbon sequestration

[$]Carbon footprint is the amount of net GHG emission (kg CO_2 eq.) per Mg of grain production

Treatment means within a column with dissimilar letters (lowercase) varied significantly ($P < 0.05$, Tukey's test)

***, **, * represent 0.1% (0.001), 1% (0.01), and 5% (0.05) level of significance, and NS represent non-significant.

7. Technological outcome/ Recommendations

7.1. Reduced Tillage Direct Seeded Rice with One-Third Wheat Residue Incorporation (RTDSR+RI)

- Among all the DSR scenarios, the reduced tillage direct seeded rice with one-third wheat residue incorporation (RTDSR+RI) showed the best overall performance. It provided an optimal balance between grain yield, resource savings (water and energy), and climate benefits (GHG mitigation and soil carbon sequestration) (Fig. 8).
- **Crop Productivity:** RTDSR+RI yielded 6.14 t ha^{-1}, which is approximately 9% lower than the conventional PTR (6.73 t ha^{-1}). However, it had a 9.96% lower cultivation cost and resulted in 8.82% lower gross returns.
- **Resource Efficiency:** This led to energy savings of 13.7% and irrigation water savings of 25.6%. It also improved EUE by 18.7% and WUE by 8.7%.
- **Soil Health:** This practice significantly enhanced soil health, increasing soil organic carbon (SOC) stocks by 26.6% and reducing soil bulk density by 1.96%.
- **Climate Impact:** This approach increased carbon input to the soil by around 50%, reduced greenhouse gas (GHG) emissions by approximately 19.8%, and lowered the carbon footprint by about 66% compared to conventional PTR.
- **Additional Benefits:** RTDSR+RI also offered improved weed control, reduced micronutrient deficiencies, and lower rodent infestation compared to Zero Tillage DSR.

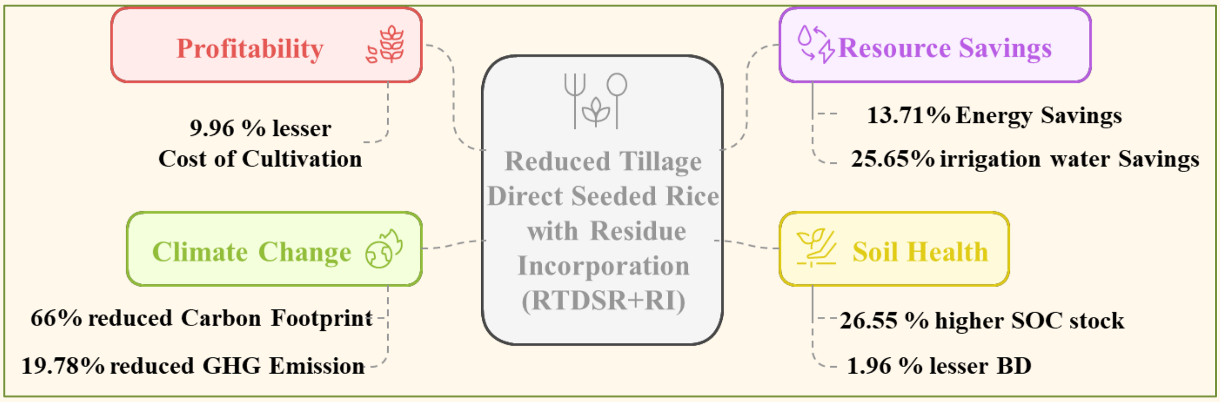


Fig. 8. The benefits of reduced tillage direct seeded rice with residue incorporation (RTDSR+RI) in comparison to conventional puddled transplanted rice.

Plate 1. Sowing of direct seeded rice Sc-3 (RTDSR+RI).

Plate 2. View of DSR crop in reduced tillage with 1/3rd residue incorporation (RTDSR+RI).

Plate 3. Harvesting of rice crop with the help of combined harver under the reduce tillage DSR with residue incorporation.

7.2. Reduced Tillage Direct Seeded Rice (RTDSR)

- The second-best performing scenario among all DSR options is Reduced Tillage Direct Seeded Rice (RTDSR). This approach offers a strong balance between grain yield, resource efficiency (water and energy savings), and climate resilience through greenhouse gas (GHG) mitigation and soil carbon sequestration (Fig. 9).
- **Crop Productivity:** RTDSR achieved a grain yield of 6.05 t ha^{-1}, which is 10.10% lower than conventional puddled transplanted rice (PTR), which yielded 6.73 t ha^{-1}. However, this was accompanied by a 9.96% reduction in cultivation costs and a 10.16% decrease in gross returns.
- **Resource Efficiency:** RTDSR resulted in a 14.02% reduction in energy consumption (55.8 GJ ha^{-1}) compared to the conventional PTR/CTW system (64.9 GJ ha^{-1}). It also saved 26.5% more irrigation water, requiring only 823 mm compared to 1119 mm in PTR.
- **Soil Health:** The practice led to a 24.9% increase in soil organic carbon (SOC) stock and a 0.65% reduction in soil bulk density (BD), contributing to improved soil structure and fertility.
- **Climate Impact:** RTDSR reduced the carbon footprint by 45.24% and lowered GHG emissions by 13.06% compared to the conventional PTR/CTW system.

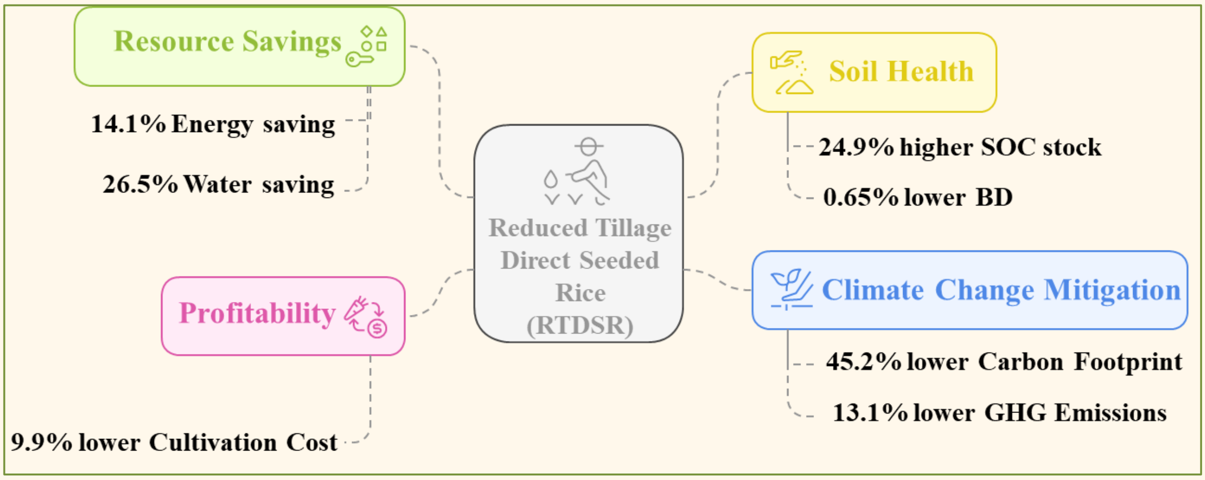


Fig. 9. The benefits of reduced tillage direct seeded rice (RTDSR) in comparison to conventional puddled transplanted rice.

7.3. Zero Tilled Wheat with One-Third Anchored Rice Residue Retention (ZTW+RR)

- Among all reduced and zero tillage wheat (ZTW) scenarios, the best performance was observed with zero tilled wheat combined with one-third anchored rice residue retention (ZTW+RR) (Fig. 10). This practice involves sowing wheat directly into anchored rice residue without burning under zero tillage conditions using a Turbo Happy Seeder (THS). The key benefits of ZTW+RR over conventional tillage wheat (CTW) are outlined below:
- **Crop Productivity:** ZTW+RR yielded 5.54 t ha^{-1}, which is 6.5% higher than the CTW (5.20 t ha^{-1}). It also resulted in a 13.3% reduction in cultivation cost and a 7.25% increase in net returns.
- **Resource Efficiency:** The practice saved approximately 6.8% of irrigation water and reduced energy consumption by 19.26%.
- **Soil Health:** ZTW+RR improved overall soil health, increasing soil organic carbon (SOC) stock by 17.11% and reducing soil bulk density.
- **Climate Impact:** This scenario offered the highest GHG mitigation among the wheat scenarios, reducing emissions by 6.2%.
- **Ease of Adoption:** ZTW+RR is highly adoptable, requiring only the Turbo Happy Seeder for zero tillage wheat sowing, making it farmer-friendly and practical.

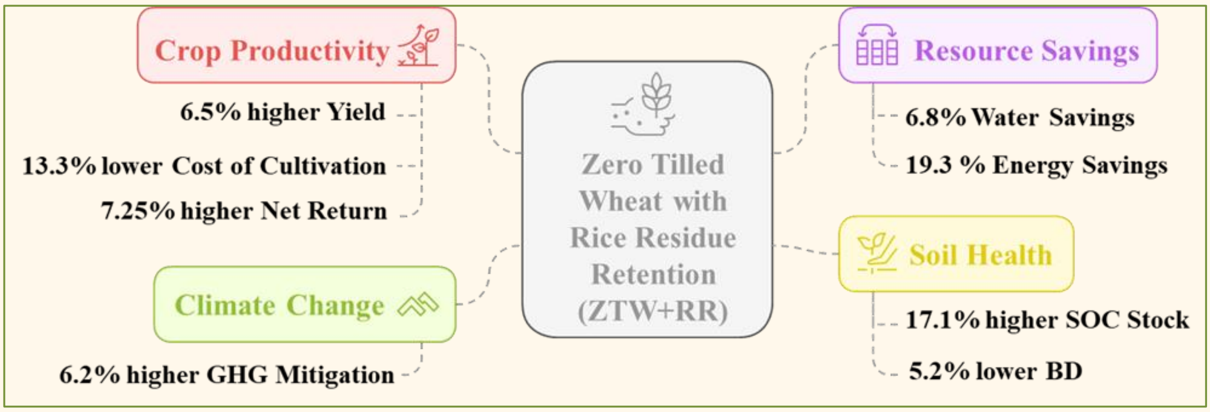


Fig. 10. The benefits of zero tillage wheat with rice residue retention in comparison to conventional tilled wheat.

Plate 4. Sowing of zero tillage wheat with rice residue retention (ZTW+RR) through happy seeder.

Plate 5. Germination of zero tillage wheat with rice residue retention.

Plate 6. Harveting of ZTW with the combined harvester.

7.4. Reduced tillage direct seeded rice followed by reduced tillage wheat with 1/3rd residue incorporation in both the crops (RTDSR+RI/RTW+RI)

- The second-best performing scenario among all DSR options is Reduced Tillage Direct Seeded Rice (RTDSR). This approach offers a strong balance between grain yield, resource efficiency (water and energy savings), and climate resilience through greenhouse gas (GHG) mitigation and soil carbon sequestration (Fig. 11).
- **Crop productivity:** This system achieved a grain yield of 11.82 t ha^{-1}, which is at par the conventional system 11.93 t ha^{-1}. Although there is reduction in DSR yield (10.1%), however it compensated by the 9.3% higher yield of wheat.
- **Crop profitability**: This system emerged as the most profitable RWS, combining the comparatively lower cultivation cost (₹74,588/ha) with high net profit (₹1,60,601/ha) and BCR (3.15).
- **Resource Efficiency:** RTDSR resulted in a 14.02% reduction in energy consumption (55.8 GJ ha^{-1}) compared to the conventional PTR/CTW system (64.9 GJ ha^{-1}). It also saved 26.5% more irrigation water, requiring only 823 mm compared to 1119 mm in PTR.
- **Soil Health:** The practice led to a 24.9% increase in soil organic carbon (SOC) stock and a 0.65% reduction in soil bulk density (BD), contributing to improved soil structure and fertility.
- **Climate Impact:** RTDSR reduced the carbon footprint by 45.24% and lowered GHG emissions by 13.06% compared to the conventional PTR/CTW system.

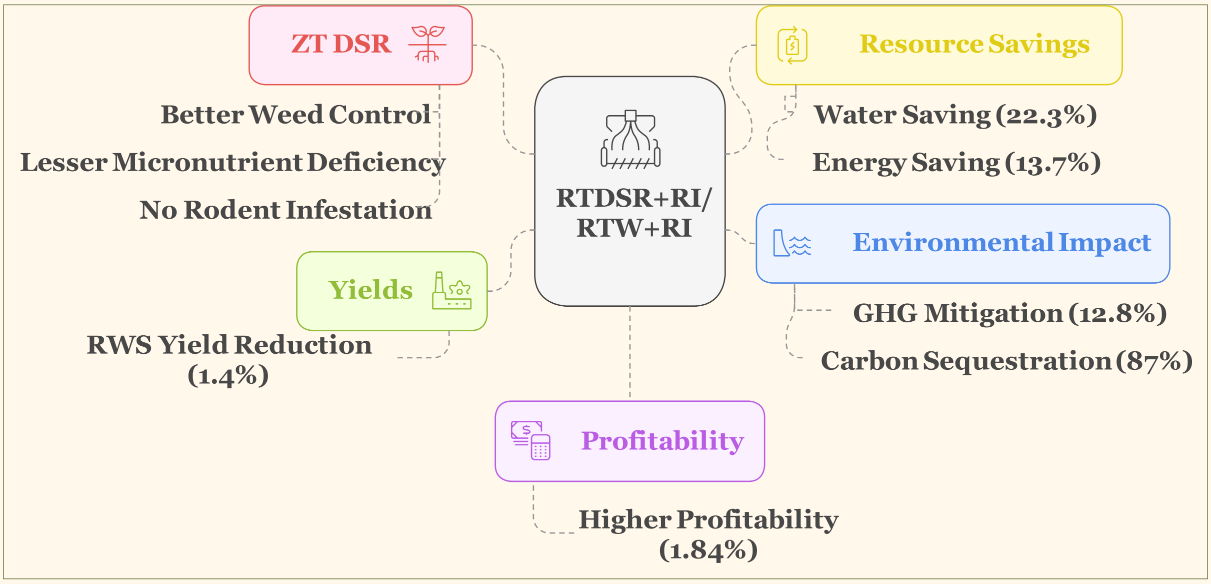


Fig. 11. The benefits of reduced tillage direct seeded rice followed by reduced tillage wheat with 1/3rd residue incorporation (RTDSR+RI/RTW+RI) as compared to conventional tilled rice-wheat system (PTR/CTW)

8. Research publications

8.1 Research papers

NAAS Rating >10

1. Fagodiya, R.K., Singh, A., Singh, R., Rani, S., Kumar, S., Rai, A.K., Sheoran, P., Chandra, P., Yadav, R.K., Sharma, P.C. and Biswas, A.K., 2023. The food-energy-water-carbon nexus of the rice-wheat production system in the western Indo-Gangetic Plain of India: An impact of irrigation system, conservational tillage and residue management. Science of The Total Environment, 860, 160428.
2. Singh, R., Singh, A., Sheoran, P., Fagodiya, R.K.*, Rai, A.K., Chandra, P., Rani, S., Yadav, R.K. and Sharma, P.C., 2022. Energy efficiency and carbon footprints of rice-wheat system under long-term tillage and residue management practices in western Indo-Gangetic Plains in India. *Energy*, 144, 122655.
3. Fagodiya, R. K., Sharma, G., Verma, K., Singh, A., Singh, R., Sheoran, P., Rai, A.K., Prajapat, K., Kumar S., Chandra P., Rani S., Sharma D. P., Yadav, R.K., Sharma, P.C., Biswas, A.K., & Chaudhari, S. K. (2024). Fourteen-years impact of crop establishment, tillage and residue management on carbon input, soil carbon sequestration, crop productivity and profitability of rice-wheat system. European Journal of Agronomy, 161, 127324.
4. Fagodiya, R. K., Sharma, G., Verma, K., Rai, A. K., Prajapat, K., Singh, R., Chandra P., Sheoran, P., Yadav, R.K., & Biswas, A. K. (2024). Computation of soil quality index after fifteen years of long-term tillage and residue management experiment (LT&RE) under rice wheat system. Agricultural Systems, 219, 104039.
5. Choudhury, S. G., Srivastava, S., Singh, R., Chaudhari, S. K., Sharma, D. K., Singh, S. K., & Sarkar, D. (2014). Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. Soil and Tillage Research, 136, 76-83.

NAAS Rating 6-10

1. Chandra, P., Fagodiya, R. K.*, Rai, A. K., Sheoran, P., Prajapat, K., Singh, A., Verma, K., Verma, V. K., Yadav, R. K., and Biswas, A. K. (2024). Different Tillage and Residue Management Practices Affect Soil Biological Activities and Microbial Culturable Diversity in Rice-Wheat Cropping System Under Reclaimed Sodic Soils. Journal of Ecological Engineering, 25(5), 193-207.
2. Singh, R., Singh, A., Kumar, S., Fagodiya, R.K.*, Sheoran, P., Rai, A.K., Rani, S. and Chandra, P., 2023. Effect of mini-sprinkler irrigation, tillage and residue on productivity, profitability and resource saving in rice–wheat system in western Indo-Gangetic Plains of India. Paddy and Water Environment, 21(4), 479-495.
3. Ranbir Singh, Ajay Singh, Satyendra Kumar, AK Rai, Sonia Rani, D K Sharma, P K Joshi, S K Chaudhary, Pardip Dey, Thimmappa K and RS Tripathi (2020).

Feasibility of mini-sprinkler irrigation system in direct seeded rice (*Oryza sativa*) in Indo-Gangetic plains of India. Indian Journal of Agricultural Sciences 90 (10): 1946–51.

NAAS Rating <6

1. Ranbir Singh, Ajay Singh, Satyendra Kumar, Parvender Sheoran, AK Rai, Sonia Rani and RK Yadav (2021). Mini-sprinkler irrigation influences water and nitrogen use efficiency and wheat yield in western Indo-Gangetic plains of India. Journal of Soil Salinity and Water Quality 13(2): 191-197.
2. Ranbir Singh, Arvind Kumar Rai, Renu Kumari, Dinesh Kumar Sharma, Satyendra Kumar, Babli and Ajay Singh (2019). Long term impact of crop residue and tillage on soil carbon, carbon sequestration, soil aggregations and wheat grain productivity under rice-wheat cropping systems on partially reclaimed sodic soils. Indian Journal of Agronomy 64(1): 11-17.
3. Renu Kumari, Ranbir Singh and Neeraj Kumar (2019). Effect of crop residue management on soil organic carbon, and soil organic matter and crop yield: An overview. *Journal of Applied and Natural science*, 11(3):712-717.
4. Ranbir Singh, Minakshi Serawat, Ajay Singh and Babli (2018). Effect of tillage and crop residue management on soil physical properties. Journal of Soil Salinity and Water Quality 10(2), 200-206.
5. Ranbir Singh, R.S. Tripathi, D.K. Sharma, S.K. Chaudhari, P.K. Joshi, P. Dey, S.K. Sharma, D.P. Sharma and Gurbachan Singh (2015). Effect of direct seeded rice on yield, water productivity and saving of farm energy in reclaimed sodic soil. *Indian Journal of Soil Conservation,* 43(3), 230-235.

8.2. Book and book chapters

1. Madhu Choudhary, Kailash Prajapat, Ram Kishor Fagodiya, Avni, SK Sanwal, HS Jat (2024) Climate Smart Agriculture (CSA) Practices for Sustainable Resource Management. pp. 439. SSPH, Delhi.
2. Ram Kishor Fagodiya*, Kamlesh Verma, Vijendra Kumar Verma (2023). Climate Resilient Agricultural Practices for Mitigation and Adaptation of Climate Change. In: Maiti et al., (eds) Social science dimensions of climate resilient agriculture. pp. 1-14, ICAR-NDRI, Karnal (ISBN no. 978-81-964762-1-2).
3. Ram K. Fagodiya, Ajay Singh, Kailash Prajapat, Priyanka Chandra, Sandeep K. Malyan, Kamlesh Verma, Vijendra Kumar Verma A.K. Rai, R.K. Yadav, A.K. Biswas (2024) Conservation agriculture practices for carbon sequestration and greenhouse gas mitigation. In: Meena et al., (eds) Waste Management for Sustainable and Restored Agricultural Soil. pp. 323-343, Elsevier, (ISBN no. 978-0-443-18486-4)
4. Fagodiya*, R. K., Sharma, G., Verma, K., Prajapat, K., Kumar, S., Kumari R. (2024) Carbon Water and Energy (CWE) Footprints of Climate Smart Agricultural

Practices. In: Choudhary et al., (eds) Climate Smart Agriculture (CSA) for Sustainable Resource Management. PP 139-156. SSPH, Delhi.

5. Chandra, P., Fagodiya, R. K.*, Singh, A., Prajapat, K., Sundha, P., Basak, N., Verma, K., Sharma G., Rai, A. K., Yadav, R.K. (2025). Advancing Sustainable Agriculture Through Plant–Microbial Interactions Amid Climate Change. In: Mann, A., Kumar, N., Kumar, A., Chandra, P., Sanwal, S.K., Sheoran, P. (eds) Cutting Edge Technologies for Developing Future Crop Plants. Springer, Singapore.
6. Ranbir Singh (2018). Resource conservation technologies for increasing crop productivity under rice–wheat cropping system. Published in book entitled" ICAR-winter School, Advances in salinity and sodicity management under different Agro-climatic regions for enhancing Farmers' income. Edited by M.J. Kaledonkar, R.L. Meena, B.L. Meena, N. Basak, P.C. Sharma. 4-24, September, 2018.
7. Ranbir Singh (2018). Practical methods of soil physical properties of salt affected soils. Published in book entitled" ICAR-winter School, Advances in salinity and sodicity management under different Agro-climatic regions for enhancing Farmers' income. Edited by M.J. Kaledhonkar, R.L. Meena, B.L. Meena, N. Basak, P.C. Sharma. 4-24, September, 2018.
8. रणबीर सिहं 2018 सुधरी क्षारीय मृदाओं में उन्नत उत्पादन विधियों द्वारा संसाधनों का संरक्षण एवं धान–गेहूँ फसल की अधिक उत्पादकता। राष्ट्रीय कृषि विकास परियोजना के अर्न्तगत –क्षमता विकास प्रशिक्षण लवण प्रभावित मृदाओ में संतुलित उर्वरक प्रबंधन, 15–17 फरवरी 2018, भाकृअनुप–केन्द्रीय मृदा लवणता अनुसंधान संस्थान,करनाल हरियाणा।

8.3. Technical folders/ popular articles

1. Ranbir Singh, D.P. Sharma, Gurbachan Singh, D.K. Sharma, S.K. Sharma, P.K. Joshi, R.S. Tripathi, P. Dey, and S.K. Chaudhari (2011). Sudhari usar bhumi mai dhan ki sidhi bijai. Technical folder No. 4/2011.
2. Ranbir Singh, S.K. Chaudhari, R.S. Tripathi, P.K. Joshi, P. Dey, S.K. Sharma, D.P. Sharma, D.K. Sharma and Gurbachan Singh (2014). Resource Conservation Technologies in Rice-Wheat System. Technical Bulletin: CSSRI/Karnal/2014/02.
3. Ranbir Singh, Ram Kishor Fagodiya, Ajay Singh, Sonia Rani, Parvender Sheoran, Arvind Kumar Rai and Priyanka Chandra (2022-23). *Paschami bharat ke sindhu-ganga maidani kshetron mein dhan gehun fasal pranali mein sanrakshan Krishi taknik*. Krishi Kiran, pp. 105-108. (*Hindi*)
4. Ranbir Singh and Satyendra Kumar (2018). Mini -Sprinkler irrigation methods in rice-wheat cropping sequence. Salinity Newsletter, 25 (1), Jan-July, 2018.
5. रणबीर सिहँ, एस.के.चौधरी, सत्येन्द्र कुमार, अरविन्द कुमार राय , प्रवेन्द्र श्योराण, आर.के.यादव एवं पी.सी.शर्मा 2018 फव्वारा सिंचाई विधि से सुधरी हुई ऊसर भूमियों में धान –गेहूँ फसल प्रणाली द्वारा पानी एवं नाइट्रोजन की बचत. प्ष्।त्.ैब्त्ध्ज्ञंतदंसध्ज्मबी थ्वसकमत 2017ध्04प
6. रणबीर सिहँ, सत्येन्द्र कुमार, प्रवेन्द्र श्योराण, अरविन्द कुमार राय, प्रियंका चंद्रा, राजेन्द्र कुमार यादव, प्रबोध चन्द्र शर्मा, सुरेश कुमार चौधरी, ए.के. बिसवास, अजय सिहँ एवं सोनिया रानी 2020 बूँद–बूँद

सिंचाई विधि द्वारा धान–गेहूँ फसल प्रणाली में अधिकतम उपज के साथ पानी एवं नत्रजन की बचत।
प्६|ट.बैत्प्ध्झंतदंसध्ज्मबी थ्वसकमत 2020ध्24

7. रणबीर सिंह अजय सिंह एवं सोनिया रानी (2020). बूँद बूँद सिचाई विधि द्वारा धान गेहू की खेती– पानी एवं उर्वरक की एक क्रन्तिकारी तकनीक । कृषि किरण 70–75.
8. रणबीर सिंह, राजेन्द्र कुमार यादव, अजय सिंह एवं सोनिया रानी (2019). धान की सीधी बिजाई तकनीक में खरपतवार नियंत्रण। कृषि किरण 27–30.

   रणबीर सिंह एवं आरऽ केऽ यादव (2017). फव्वारा सिंचाई विधि से सुधरी हुई ऊसर भूमियों में धान –गेहूँ फसल प्रणाली द्वारा पानी एवं नाइट्रोजन की बचत । कृषि किरण ;9द्ध 75–79

8.4. Abstract published in conference and seminar

1. Ram Kishor Fagodiya*, Kamlesh Verma, Gargi Sharma, Kailash Prajapat, Priyanka Chandra, A. K. Rai, R. K. Yadav (2025). Greenhouse gases mitigation and carbon sequestration potential of rice-wheat system: An impact of long-term tillage and residue management experiment (LT&RE) in 1st International Farming Systems Conference (IFSC 2025) "Transforming Food, Land and Water Systems under Global Climate Change" held at ICAR-Indian Institute of Farming System Research, Modipuram during 7-9th March, 2025.
2. Ram Kishor Fagodiya*, Kamlesh Verma, Gargi Sharma, Kailash Prajapat, Priyanka Chandra, A. K. Rai, Ranbir Singh, R. K. Yadav, A. K. Biswas (2024). Long-term tillage and residue management in rice-wheat system: An impact on greenhouse gases mitigation and carbon sequestration in National Conference on SHASHWAT SRISHTI SANRAKSHAN "A Pledge for Protecting World against Natural Hazards: Agro-biotechnological Approach Organized by SSCE at at ICAR-Central Agroforestry Research Institute, Jhansi during August 23-24, 2024.
3. Ram K. Fagodiya*, Arvind Kumar Rai, Kailash Prajapat, Priyanka Chandra, Gargi Sharma, Kamlesh Verma, Parvender Sheoran and Rajender Kumar Yadav (2024). Assessment of Soil Health of DSR-ZTW system in Reclaimed Sodic Soil under Long-term Tillage and Residue Management Experiment (LT&RE). Presented in International Salinity Conference (ISC - 2024) on "Rejuvenating Salt Affected Ecologies for Land Degradation Neutrality under Changing Climate held at ICAR-Central Soil Salinity Research Institute, Karnal during 14th – 16th February, 2024.
4. Ram K. Fagodiya*, Ranbir Singh, Arvind Kumar Rai, Kailash Prajapat, Priyanka Chandra, Gargi Sharma, Kamlesh Verma, Parvender Sheoran and Rajender Kumar Yadav (2024). Water-Energy-Carbon (WEC) Nexus Gain of Rice-Wheat System: An assessment of Long-term Tillage and Residue Management Practices. Presented in International Salinity Conference (ISC - 2024) on "Rejuvenating Salt Affected Ecologies for Land Degradation Neutrality under Changing Climate held at ICAR-Central Soil Salinity Research Institute, Karnal during 14th – 16th February, 2024.
5. Ram Kishor Fagodiya, Arvind Kumar Rai, Kailash Prajapat, Priyanka Chandra, Kamlesh Verma, Vijendra Kumar Verma (2023). Critical Carbon Input and Carbon Sequestration Potential of Long-term Tillage and Residue Management

Practices in Rice–Wheat System. Presented in 5th International Conference on "Sustainable Natural Resource Management Under Global Climate Change (SCSI 2023) held at National Agricultural Science Centre (NASC) Complex, New Delhi during 7th -10th November, 2023.

6. Fagodiya R.K., Singh R., Rai A.K., Sheoran P., Chandra P., Singh A. & Rani S. (2022). Water footprint and greenhouse gases emission in rice-wheat cropping system of western Indo-Gangetic Plains of India: An impact of irrigation, tillage and residue. Presented in the International Conference on "Integrated Approaches in Science & Technology for Sustainable Future (IASTSF-2022)" held during 28th Feb.-1st March, 2022 at J. C. Bose University of Science and Technology, YMCA, Faridabad, Haryana, India.
7. Fagodiya R.K., Singh R., Rai A.K., Sheoran P., Chandra P., Singh A. & Rani S. (2022). Environmental Footprint of Rice-Wheat Production System in Pressurized Irrigation, Tillage, and Residue Management practices" presented in the 6th National Conference on "Salinity Management for Land Degradation Neutrality and Livelihood Security under Changing Climate" held during 11-13 October, 2022 held at ADAC&RI, Tiruchirappalli (TN).
8. Fagodiya, R.K., Singh, R., Sheoran, P., Rai, A.K., Chandra, P., Singh, A., Rani, S. (2021). Energy budgeting under conservation tillage with residue management in rice-wheat cropping system in North-West India. In: Fifth International Agronomy Congress on "Agri-Innovations to Combat Food and Nutrition Challenges" held at PJTSAU, Hyderabad during 23-27 November 2021.

8. Infrastructure development and equipment procured

- The following infrastructure, equipment, and other facilities have been developed at the ICAR-CSSRI centre to support scheduled conservation agriculture research activities:
- Procured a no-till planter, happy seeder machine for reduced tillage and zero tillage practices
- Procured instruments for soil physical parameter analysis viz. Soil moisture meter (TDR-350), Digital Soil Penetrometer (SC-900), and Hydraulic soil core sampler.
- Procured field weighing balances, Double ring soil infiltrometer, Parshall Flume, and Yoder's apparatus.
- Procured Double distillation water Unit, LCD Display Orbital Shaking Incubator, and Kjeldahl digestion cum distillation assembly unit with fume hood
- Procured lab instruments viz. pH Meter, conductivity meter, ovens, hot plates, weighing balances, Refrigirator flame photometer etc
- Procured Computer, UPS, Printer, Room air conditioner and other miscellaneous equipments.

Happy seeder zero till drill machine

Orbital Shaking Incubator

Laboratory and Field weighing balances

Parshall flume

Double ring soil infiltrometer

pH meter

Electrical conductivity meter

Nitrogen Management Through Leaf Colour Chart (LCC)

Kjeldahl digestion cum distillation assembly unit with fume hood

Hydraulic soil core sampler

Digital Soil Penetrometer (SC-900)

Soil moisture meter (TDR-350)

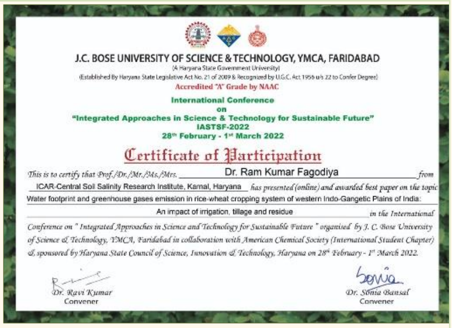
Flame photometer

Yodder Apparatus

9. Awards and honour received

Young Scientist Award (2023) of Farming System Research and Development Association, Modipuram, Meerut.

Young Scientist Award (2023) of The Society for Science of Climate Change and Sustainable Environment (SSCE), New Delhi



Best paper presentation awards in seminar, symposia and conferences

10. VIPs visit at CRP on CA Experiment

Plate 7. Visit by ICAR DG (Dr. Himanshu Pathak) at CRP on CA field experiment.

Plate 8. Visit by ICAR DG Dr. Trilochan Mohapatra and DDG (NRM), Dr. Suresh Kumar Chaudhari

Plate 9. Visit by Dr. Ashis Kumar Biswas, Lead Centre Platform Coordinator

11. References

Bhatt, R., Kukal, S. S., Busari, M. A., Arora, S., & Yadav, M. (2016). Sustainability issues on rice–wheat cropping system. *International Soil and Water Conservation Research, 4*(1), 64–74.

Chauhan, B. S., Mahajan, G., Sardana, V., Timsina, J., & Jat, M. L. (2012). Productivity and sustainability of the rice wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: Problems, opportunities, and strategies. In *D. L. Sparks (Ed.), Advances in Agronomy* (Vol. 117, pp. 315–369). Elsevier.

Fagodiya, R. K., Sharma, G., Verma, K., Rai, A. K., Prajapat, K., Singh, R., Chandra, P., Sheoran, P., Yadav, R. K., & Biswas, A. K. (2024). Computation of soil quality index after fifteen years of long-term tillage and residue management experiment (LT&RE) under rice wheat system. *Agricultural Systems, 219*, 104039. https://doi.org/10.1016/j.agsy.2023.104039

Fagodiya, R. K., Sharma, G., Verma, K., Singh, A., Singh, R., Sheoran, P., Rai, A. K., Prajapat, K., Kumar, S., Chandra, P., & Rani, S. (2024). Fourteen-years impact of crop establishment, tillage and residue management on carbon input, soil carbon sequestration, crop productivity and profitability of rice-wheat system. *European Journal of Agronomy, 161*, 127324. https://doi.org/10.1016/j.eja.2024.127324

Farooq, M. (2023). Conservation agriculture and sustainable development goals. *Pakistan Journal of Agricultural Sciences, 60*(3). https://doi.org/10.21162/PAKJAS/23.170

Friedrich, T., Derpsch, R., & Kassam, A. H. (2012). Overview of the global spread of conservation agriculture. *Field Actions Science Reports*, (Special Issue). http://journals.openedition.org/factsreports/1941

Jain, N., Bhatia, A., & Pathak, H. (2014). Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research, 14*(1), 422–430. https://doi.org/10.4209/aaqr.2013.01.0031

Kassam, A., Derpsch, R., & Friedrich, T. (2020). Development of conservation agriculture systems globally. *Food and Agriculture Organization of the United Nations (FAO)*. https://doi.org/10.19103/AS.2019.0048.02

Lal, R. (2013). Intensive agriculture and the soil carbon pool. *Journal of Crop Improvement, 27*(6), 735–751. https://doi.org/10.1080/15427528.2013.845050

Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: A global perspective—A review article. *Agriculture and Food Security, 10*(1), 1–25. https://doi.org/10.1186/s40066-021-00323-8

Pathak, H., Ladha, J. K., Aggarwal, P. K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S. K., Mishra, B., Sastri, A. S. R. A. S., Aggarwal, H. P., Das, D. K., & Gupta, R.

K. (2003). Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Research, 80*(3), 223–234. https://doi.org/10.1016/S0378-4290(02)00196-2

Pratibha, G., Srinivas, I., Rao, K. V., Raju, B. M. K., Thyagaraj, C. R., Korwar, G. R., Venkateswarlu, B., Shanker, A. K., Choudhary, D. K., Rao, S. K., & Srinivasarao, Ch. (2015). Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeon pea-castor systems. *European Journal of Agronomy, 66*, 30–40. https://doi.org/10.1016/j.eja.2015.02.004

Sidhu, H. S., Singh, M., Singh, Y., Blackwell, J., Lohan, S. K., Humphreys, E., Jat, M. L., Singh, V., & Singh, S. (2015). Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research, 184*, 201–212. https://doi.org/10.1016/j.fcr.2015.09.010

Singh, A., Nandal, D. P., & Punia, S. S. (2017). Performance of sequential herbicides to control weeds in direct seeded rice. *Journal of Applied and Natural Science, 9*(3), 1324–1328. https://doi.org/10.31018/jans.v9i3.1433

Singh, R., Singh, A., Sheoran, P., Fagodiya, R. K., Rai, A. K., Chandra, P., Rani, S., Yadav, R. K., & Sharma, P. C. (2022). Energy efficiency and carbon footprints of rice-wheat system under long-term tillage and residue management practices in western Indo-Gangetic Plains in India. *Energy, 244*, 122655. https://doi.org/10.1016/j.energy.2022.122655

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development* (General Assembly Resolution A/RES/70/1). https://sdgs.un.org/2030agenda

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